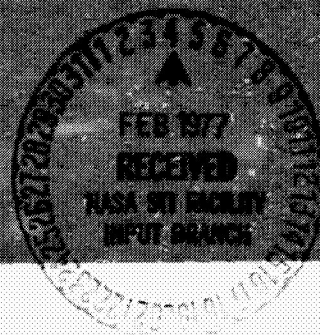


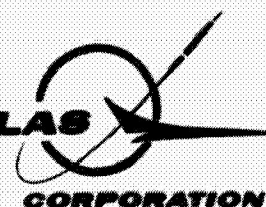
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TECHNOLOGY AIRCRAFT DESIGN DEFINITION STUDY.
VOLUME 2: PROPELLSION TRANSMISSION SYSTEM
DESIGN (MCDONNELL AIRCRAFT CO.) 60 P
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LIFT/CRUISE FAN V/STOL

TECHNOLOGY AIRCRAFT

DESIGN DEFINITION STUDY

VOLUME II

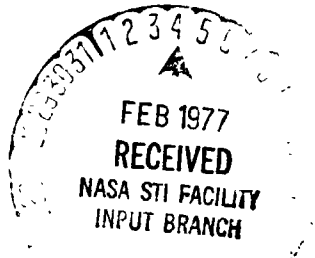
PROPULSION TRANSMISSION SYSTEM DESIGN

Revision letter

Contract number NAS2-9245

Prepared by

Wm. J. O'Brien



MCDONNELL AIRCRAFT COMPANY

Box 516, Saint Louis, Missouri 63166 -- Tel. (314)232-0232

MCDONNELL DOUGLAS

CORPORATION

MDC A4551
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INTRODUCTION AND SUMMARY

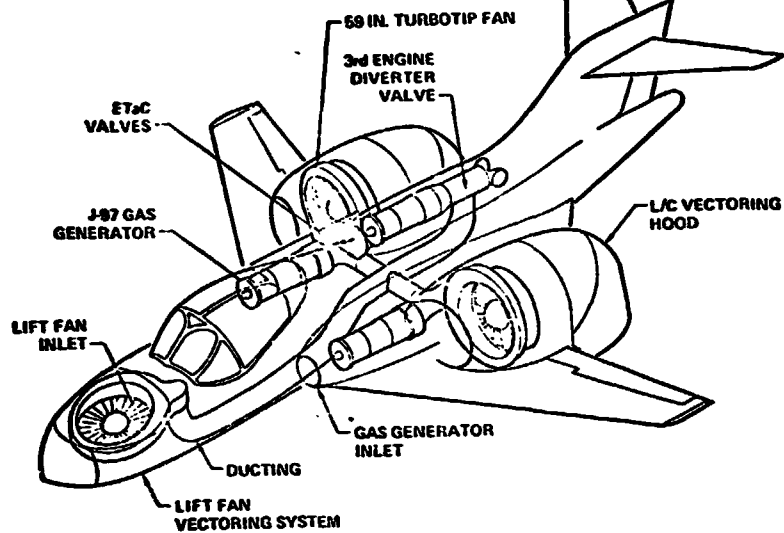
This report presents results of Task III of a study by McDonnell Aircraft Company (MCAIR) for NASA Ames Research Center and the U.S. Navy to conceptually design two types of Lift/Cruise Fan Technology Aircraft. One aircraft used turbotip fans pneumatically interconnected to three gas generators and the other aircraft used variable pitch fans mechanically interconnected to three turboshaft engines. The objective of Task III was to analyze and design the components of each propulsion transmission system to the depth necessary to determine areas of risk, development methods, performance, weights and costs. The types of materials and manufacturing processes were identified to show that the designs followed a low cost approach. The lift/cruise fan thrust vectoring hoods, which are applicable to either aircraft configuration, were also evaluated to assure a low cost/low risk approach.

The turbotip propulsion system consists of three General Electric (G.E.) LCF459 turbotip fans powered by three G.E. YJ97 gas generators through the Energy Transfer and Control (ETaC) system. The ETaC system consists of ducting, bellows and control valves. The ducting system for an operational aircraft would be a MCAIR developed light weight, composite design; however, stainless steel was selected for the RTA to assure a low cost/low risk approach. The stainless steel ducting is approximately 500 lb heavier than a composite construction but the excess thrust margin available in the turbotip RTA allows this approach to be used. A single duct was installed for the lift fan to reduce cost. The operating temperature, 1260°F, is nearly the same as that already demonstrated by the XV-5 aircraft thereby minimizing risk. An evaluation of the ETaC system components indicated that all could be fabricated from existing materials using standard fabrication procedures.

The mechanical propulsion system consists of three Hamilton Standard variable pitch fans powered by three Detroit Diesel Allison (DDA) XT701 turboshaft engines through a mechanical transmission system. This system includes shafting, supports, combiner gearbox, lift fan clutch and an over-running clutch for the third engine. The design and analysis of the mechanical transmission system was subcontracted to DDA to utilize their expertise as a leading designer and fabricator of power transmission components. Based on MCAIR guidelines, which included the use of standard materials and state-of-the-art sizing criteria, DDA arrived at a low risk design for the mechanical transmission system.

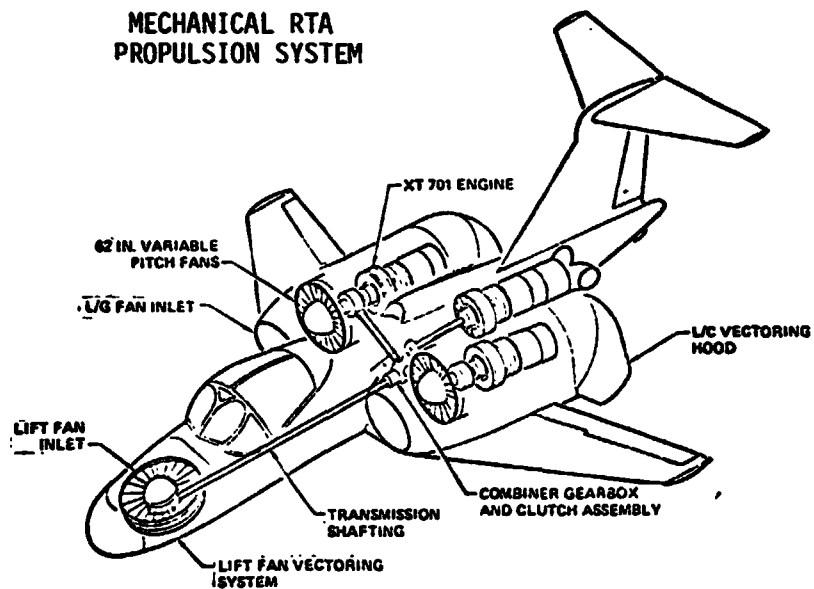
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**TURBOTIP RTA
PROPULSION SYSTEM**



The design and analysis of the turbotip and mechanical transmission systems and the thrust vectoring hoods demonstrated that state-of-the-art materials and fabrication procedures can be used, thereby assuring a low cost/low risk approach for the RTA.

**MECHANICAL RTA
PROPULSION SYSTEM**



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1. TURBOTIP TRANSMISSION SYSTEM

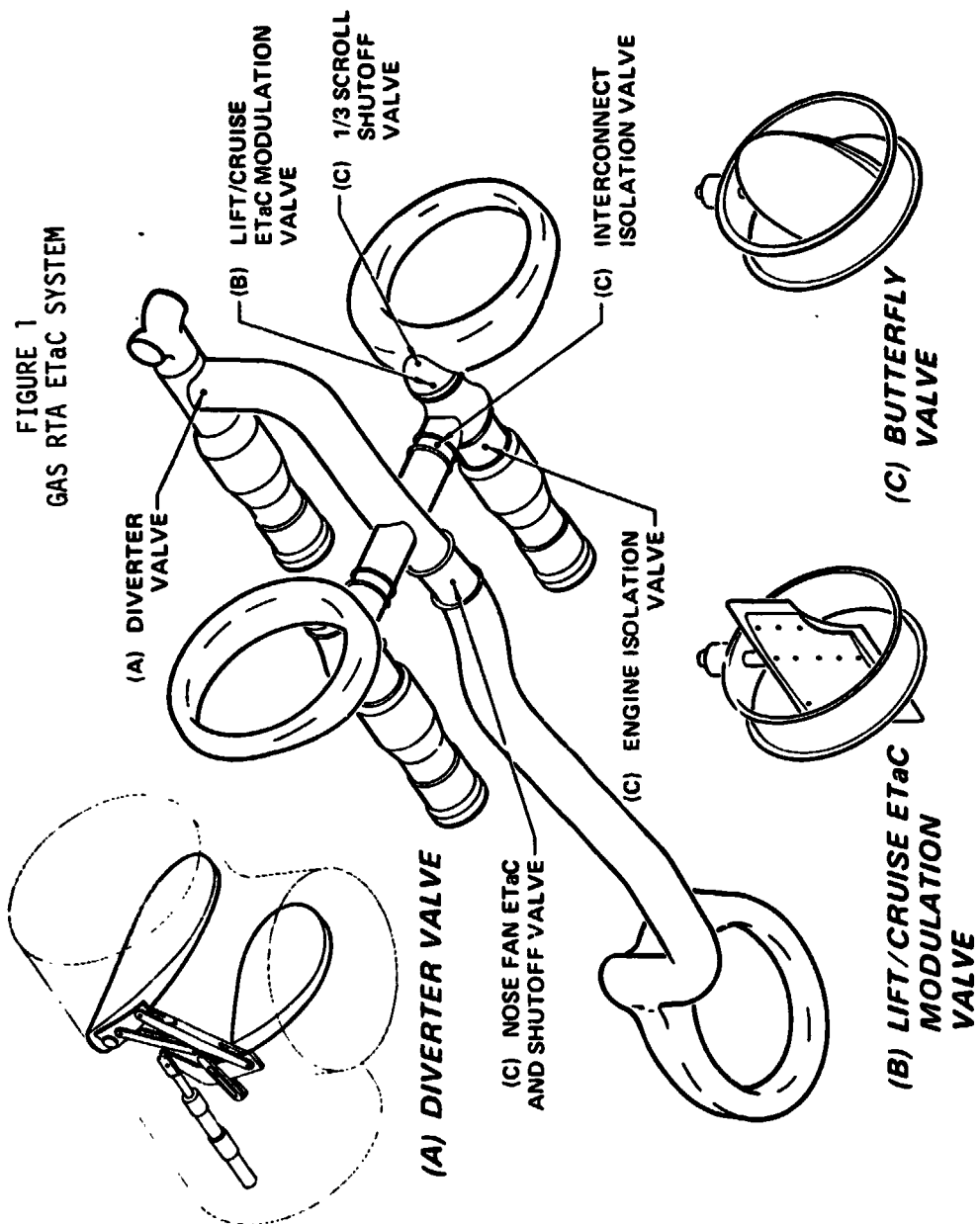
1.1 GENERAL DESCRIPTION

The Energy Transfer and Control (ETaC) system is used to distribute and control the exhaust gas from the General Electric (G.E.) iJ97 gas generators to the three G.E. LCF459 turbotip fans. This integrated duct system, Figure 1, consists of: ducting, valves for control and/or shutoff, and a system of bellows joints for thermal expansion compensation. The ETaC system distributes the high energy gas from the engines to perform the following functions:

- (a) Distribution of the gas to the turbotip fans
- (b) Provides the proper distribution for control during takeoff and conversion
- (c) Provides for gas transfer in the event of an engine failure
- (d) Isolates and bypasses the failed portion of the system from the active portion
- (e) Provides the proper distribution of gas for cruise and high speed flight
- (f) Allows the third engine to be isolated from the main system after "V" takeoff or to be brought back on line for a "V" landing.

To assure a low cost/low risk approach, two major guidelines were established: (1) use stainless steel ducting, and (2) use only one duct for the lift fan. The use of stainless steel ducting results in a weight penalty of approximately 500 lb as compared to the MCAIR developed composite ducting but provides for a low risk development program using state-of-the-art fabrication procedures. The single duct to the lift fan is a low cost approach employed for the RTA. This single duct approach also allowed the scrolls of all fans to be identical with the exception of the entry segment.

The overall ETaC system design was coordinated with various speciality manufacturers to assure simplicity of fabrication. These manufacturers included Metal Bellows Co., Stainless Steel Products, and Arrowhead Products. A layout of the ETaC system, Drawing RTA 260-001-4, was prepared to assure that the system components interfaced properly with each other and with the fan scrolls. This design was coordinated with G.E. Each of the major components were designed and evaluated and are discussed in the following paragraphs.



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1.2 SYSTEM SELECTION

In an aircraft power transmission system, it is necessary to make provisions for misalignments in the energy transmitting components. In order to compensate for these misalignments in the turboprop system with essentially no leakage, bellows are installed at the required locations. The bellows serve to relieve the effects of misalignment which are caused by differences in thermal expansion between the ducts and adjacent fuselage structure, nominal manufacturing tolerances in the vehicles, and normal aircraft structural deflections during flight. The design of an optimum ducting system, providing these functions, includes consideration as to the type of bellows system to be installed, i.e., a compression or tension system.

A compression system, which may appear attractive because of its apparent simplicity in utilizing unsophisticated ducting components, is one in which the bellows are not restrained. The insertion of the bellows in the line, however, destroys its ability to cancel the duct pressure loads against each other through axial tension in the ducting walls, since the bellows will stretch rather than carry the tension. This necessitates strong brackets and backup structure to react these loads. In the RTA system with a maximum working pressure of 63 psia and an effective bellows area of 257 in.² (for a 17-inch diameter duct), this columnar action amounts to a design load of 24,300 lb. The fact that the pressure reaction bracketry and reacting fuselage structure becomes necessarily heavy is apparent from the magnitude of the design load. In addition to this undesirable feature, the system also places the ducting in column action requiring strength in the walls of the duct beyond that required to carry the hoop tension created by the internal pressure.

A tension system is one in which the thermal expansion bellows components are restrained from stretching while under internal pressure, by means of self-contained tension links, or by means of an interlocking system of bellows to balance the pressure separating load. The tension system drastically reduces the number, complexity and weight of the ducting supports and allows a reduction in gage of the duct walls by eliminating the column action on the ducts when compared to a compression system. The tension system was considered the lowest risk approach and therefore was selected for the RTA.

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1.3 DUCTING SYSTEM

The ducting system is of stainless steel construction, wrapped with a thermal insulation blanket, and consists of straight sections, transition sections, elbows and supports.

1.3.1 DUCTING - Figure 2 illustrates the ducting configuration selected for the gas distribution system. The duct consists of a continuous inner wall covered by a second wall or lamination which is beaded every six to eight inches. These beads provide stiffness to protect against collapsing from conditions of high internal pressure differential or from handling during installation or inspection. The inner and outer walls are joined together by seam welds between the beads to improve the sectional stiffness. Pressure buildup between the inner and outer shell is relieved by venting the outer shell to ambient through small holes drilled in the beads. The entire duct is wrapped with an insulation blanket which is wire-laced in place.

1.3.2 ELBOWS - Discussions with duct component fabricators and MCAIR producibility specialists indicated that the most practical and simple process for fabricating the elbows is by hydroforming short sections, and then butt welding each section to the other to form the complete elbow. Thicker material was used in the elbow area to compensate for any thinning which may occur during the hydroform process. If a weight reduction becomes desirable, selective chemical milling can be used to reduce the weight of the heavier sections.

1.3.3 TRANSITION SECTIONS - The 'Y' transition section will be hydroformed from flat stock (Inconel 617 or equivalent) into sections and then butt welded in a fixture to make the required assembly shown in Figure 3. This neutral assembly is used in both the right hand and left hand application.

The transition section at the intersection of the third engine duct with the crossover duct can likewise be fabricated by hydroforming.

The weight of each of these sections could also be reduced, if desired, by selective chem milling.

1.3.4 SUPPORTS - In order to establish the types and locations of the bellows assemblies in the system, certain fixed points were assumed, and supports were designed at these points to provide for operation in the anticipated maneuvering and vibrational environments. In order to provide protection for the ducts and adjacent structure, fixed, sliding and swinging supports are required. These supports are designed to absorb the acceleration loads but not interfere with the deflection capabilities of the ducts. The types of support which have

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FIGURE 2
DUCTING CONFIGURATION

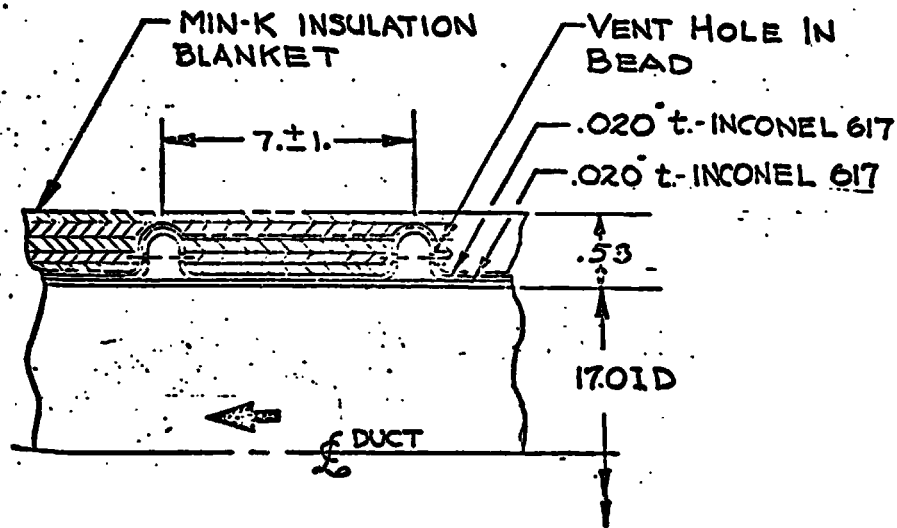
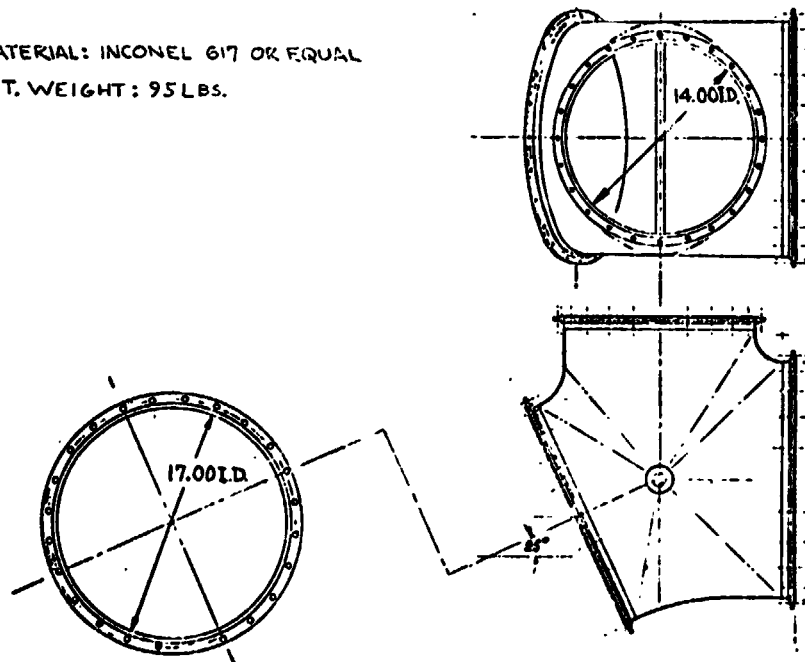


FIGURE 3
M260-RTA-1
GAS DISTRIBUTION SYSTEM 'Y' DUCT ASSEMBLY

MATERIAL: INCONEL 617 OR EQUAL
EST. WEIGHT: 95 LBS.



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been designed are illustrated in Figures 4 through 8 and indicate the simplicity of the assemblies.

1.3.5 THERMAL INSULATION -- The following requirements and operating conditions were used in the heat transfer analysis to determine the thickness and weight of the ducting external insulation:

Duct temperature	1260°F
Ambient temperature*	100°F
Duct diameter	17 inches
Maximum external insulation temperature	300°F
*Natural convection only was assumed, and the fuselage was constantly purged of hot air to maintain 100°F ambient conditions	

The results indicated that in order to remain within the specified surface temperature of the insulation blanket, 0.53 inch of Min-K insulation was required around the periphery of the duct. In addition, a high emissivity coating was required on the external surface of the blanket.

The insulation assembly consists of removable blankets of foil-encapsulated batting, with capstans provided for installation by wire lacing and breather vents to equalize pressure variations. The calculated weight of the blanket for the 17 inch diameter duct is 5.72 lb/ft run.

Min-K insulation exhibits the lowest thermal conductivity of the available materials for this application; however, other insulations could provide the same protection at a lower weight if increased thickness were acceptable. For example, a thickness of 0.90 inch of KAOWOLL (8 PCF) could be used and the insulation system weight would be reduced to 4.33 lb/ft run. Due to installation consideration Min-K insulation was selected.

1.3.6 BELLOWS - The bellows assemblies designed for the RTA fall into two categories. One group of bellows absorbs the thermal expansion by angulation movements, the other group through axial motion.

The joints which absorb thermal growth by angulation are referred to as angulation bellows and are of two types. The pin joint type which is capable of deflection or angulation in one direction only and the fully articulated or gimbal joint which allows for deflection in any direction.

The joints which absorb thermal growth by axial motion are called compensators since a system of interlocking and balanced bellows can compensate for the ducting pressure load or thermal growth without exerting its compressive end load on the adjacent duct sections or the supporting structure. The gimbal

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FIGURE 4
MAIN ANCHOR SUPPORT

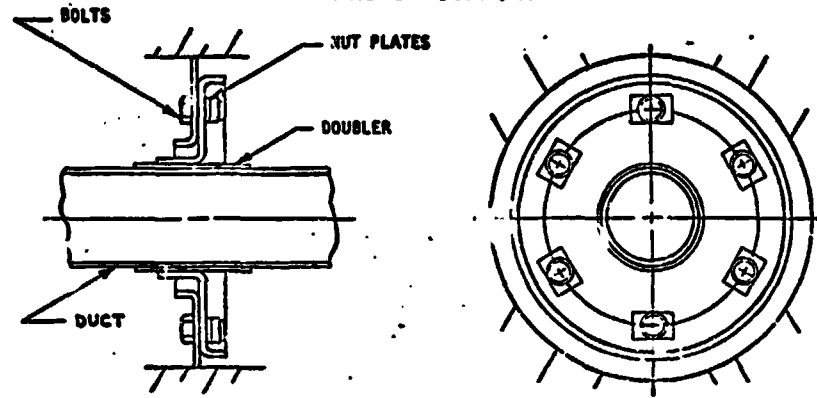


FIGURE 5
SWINGING SUPPORT - LINKAGE

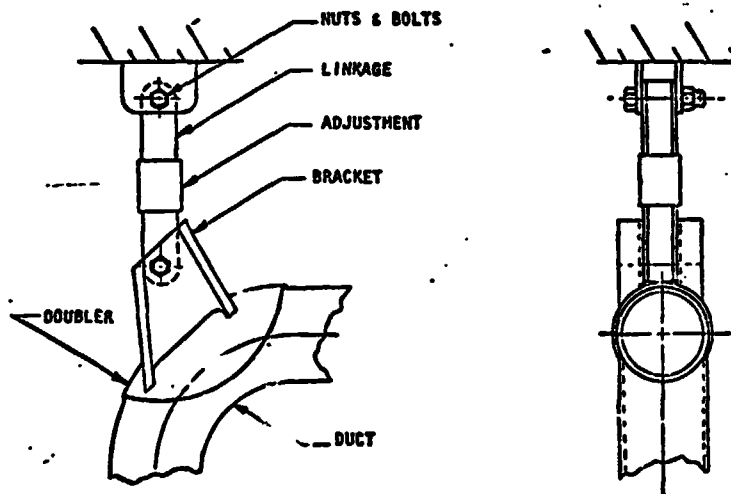
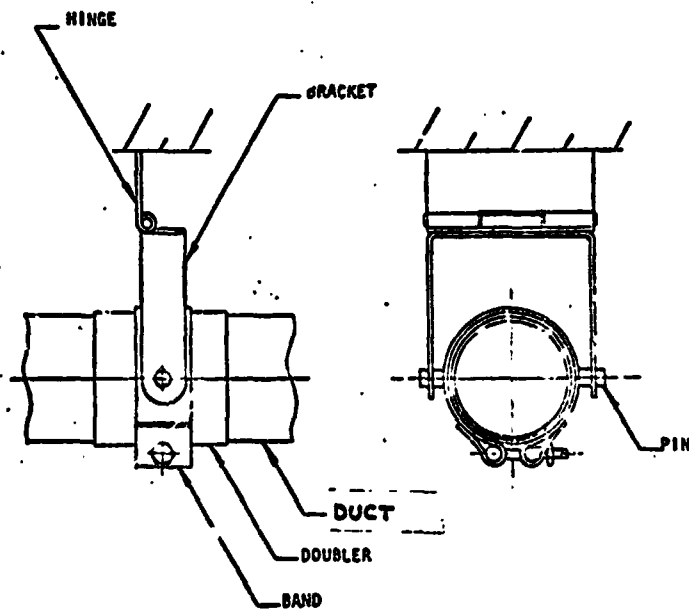


FIGURE 6
SWINGING SUPPORT - HINGE



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FIGURE 7
SLIDING SUPPORT - BOLT TYPE

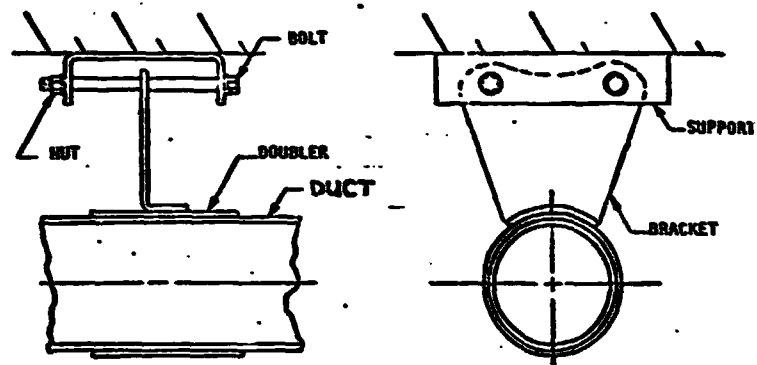
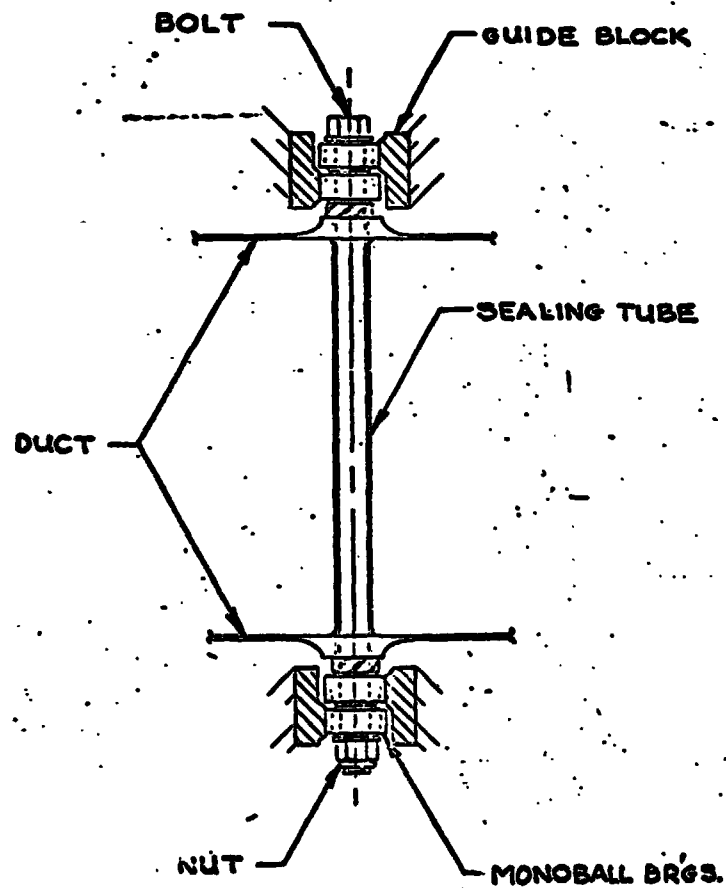


FIGURE 8
DIRECTIONAL ANCHOR - ROLLING SUPPORT



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joint is detailed on Figure 9.

In addition to the above mentioned bellows components the RTA gas distribution system makes use of two sets of free bellows, called bellows sets. This component allows the engine/cruise fan assembly to move free of the interconnect system without inducing excessive bending moments in the engine case. This arrangement of bellows consists of splitting one long bellows into two halves and putting an intermediate spool between them so that the bellows can adjust to a parallel offset condition with reduced shear loads and end moments. The piston load in the bellows is reacted by the main anchor point on the centerline of the aircraft and the directional anchor on the 'Y' duct, to which the bellows set is attached. This arrangement is shown in Figure 10. All bellows components on the RTA are equipped with internal sleeves to reduce the pressure drop across the joint.

1.4 VALVES

All the valves in the distribution system are of the "butterfly" type, consisting of a valve body with attaching flanges, a closure or modulation vane mounted on a torque shaft, and a shaft sealing gland. Since the RTA will have ample thrust to permit small amounts of leakage without penalizing the overall thrust schedule, a simple low cost approach which will permit small amounts of leakage will be employed in the design of the valve seats. The valves, which provide for the isolation of components or modulation of the gas flow, are described in the following paragraphs and are shown installed on MCAIR Drawing RTA 260-001-4.

1.4.1 ENGINE ISOLATION VALVE - The two engine isolation valves operate only during the engine out condition. The valves rotate through an angle of 90 degrees to prevent a back flow of hot gas through an inoperative engine. The inside diameter of the valves is 17 inches.

1.4.2 ENGINE ETaC MODULATION VALVE - These two valves modulate gas to the lift/cruise fan scrolls and are not required to close against the valve case. They rotate through an angle of approximately 30 degrees, depending on the modulation required for control. The valve design is illustrated in Figure 11.

1.4.3 ENGINE ETaC AND SHUTOFF VALVE - This valve serves to both modulate and close off the flow. It is located on the centerline of the aircraft just forward of the interconnect duct, preventing pressurization of the nose fan scroll ducting during the cruise mode or modulating the flow to the nose fan in powered lift operation. The valve rotates through an angle of 90 degrees for sealing. The valve design is illustrated in Figure 12.

FIGURE 9
M260-RTA-1
ENGINE/FAN GAS DISTRIBUTION ANGULATION BELLOWS

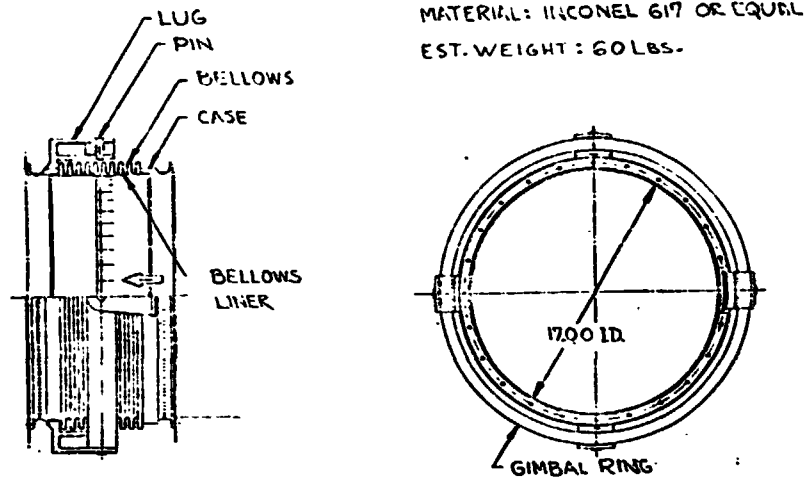
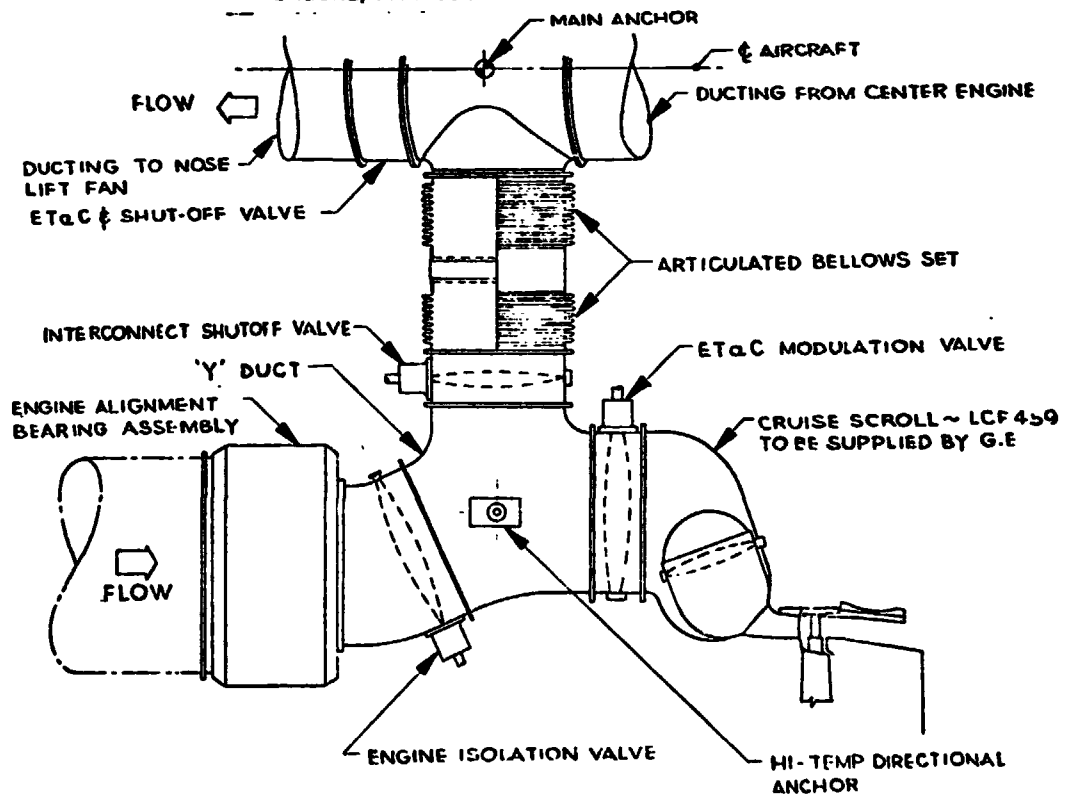


FIGURE 10
ENGINE/FAN COUPLING ARRANGEMENT



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FIGURE 11
M260-RTA-1
ETaC MODULATION & GAS DISTRIBUTION VALVE

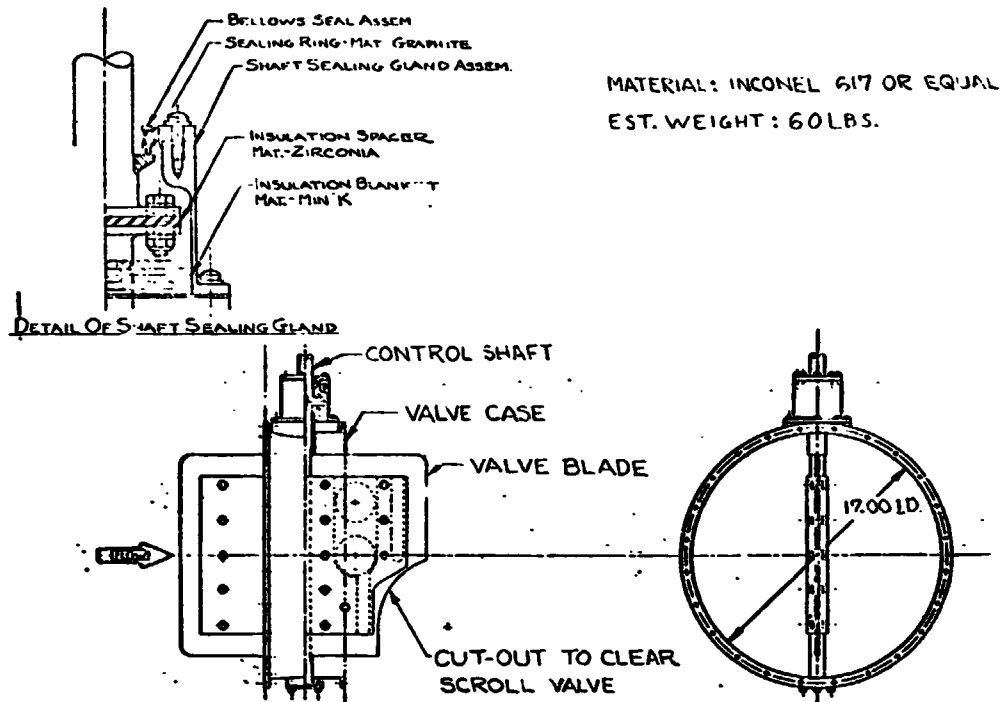
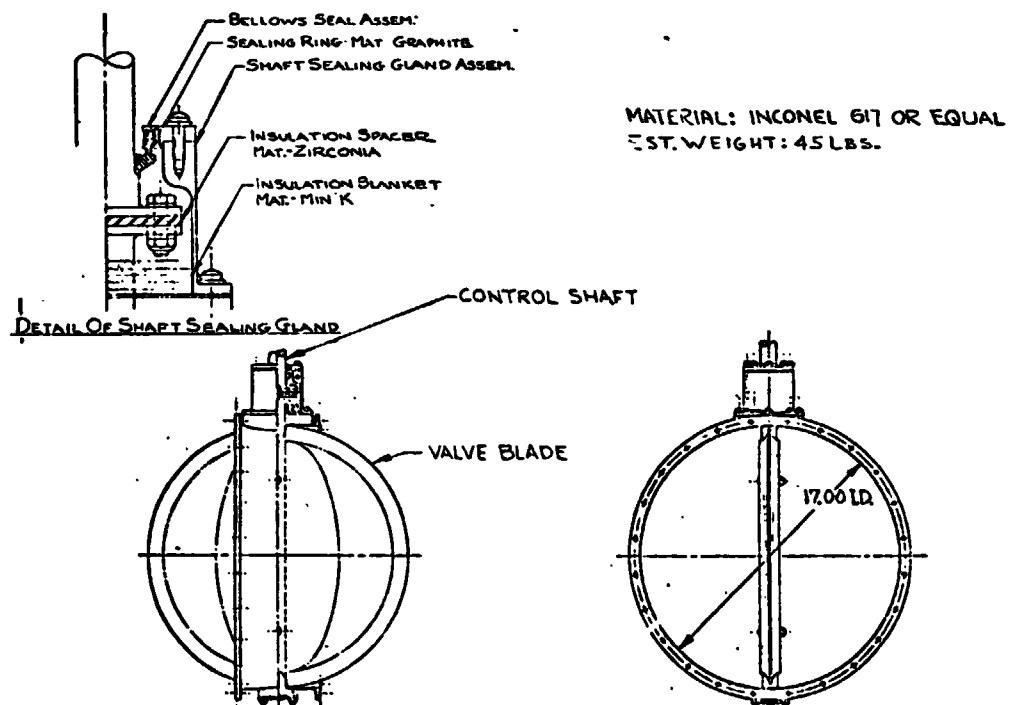


FIGURE 12
ETaC + SHUT OFF GAS DISTRIBUTION VALVE



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1.4.4 INTERCONNECT ISOLATION VALVES - These two valves are used during engine start-up and in the cruise mode to isolate the lift/cruise fans when no modulation is required. The valves rotate through an angle of 90 degrees to close off the flow. The inside diameter of the valves is 14 inches.

1.4.5 DIVERTER VALVE - The diverter valve is used to direct the hot turbine exhaust gases from the third gas generator either to the nose lift fan (and to the cruise fan in engine-out emergency) or to conventional fixed engine exhaust nozzles. The diverter valve has a bifurcated valve body, two closure doors and shafts, an inlet diffuser cone, and a closure door actuation system. The inside diameter of the valves is 17 inches. This valve is essentially identical to the design used in the XV-5 aircraft.

The closure doors are actuated by a set of linkages located outside the valve body. When the doors are in the diverted position, the exhaust gases are directed through the diverted leg of the valve to the nose fan system, and the exit to the engine exhaust nozzle is sealed off, as shown on MCAIR Drawing RTA 260-001-4. In the straight-through (or cruise mode) position, the ducts to the fan system are closed off and the engine exhaust is directed through the exhaust nozzle.

1.5 ENGINE DIFFUSER AND ALIGNMENT BEARINGS SECTION

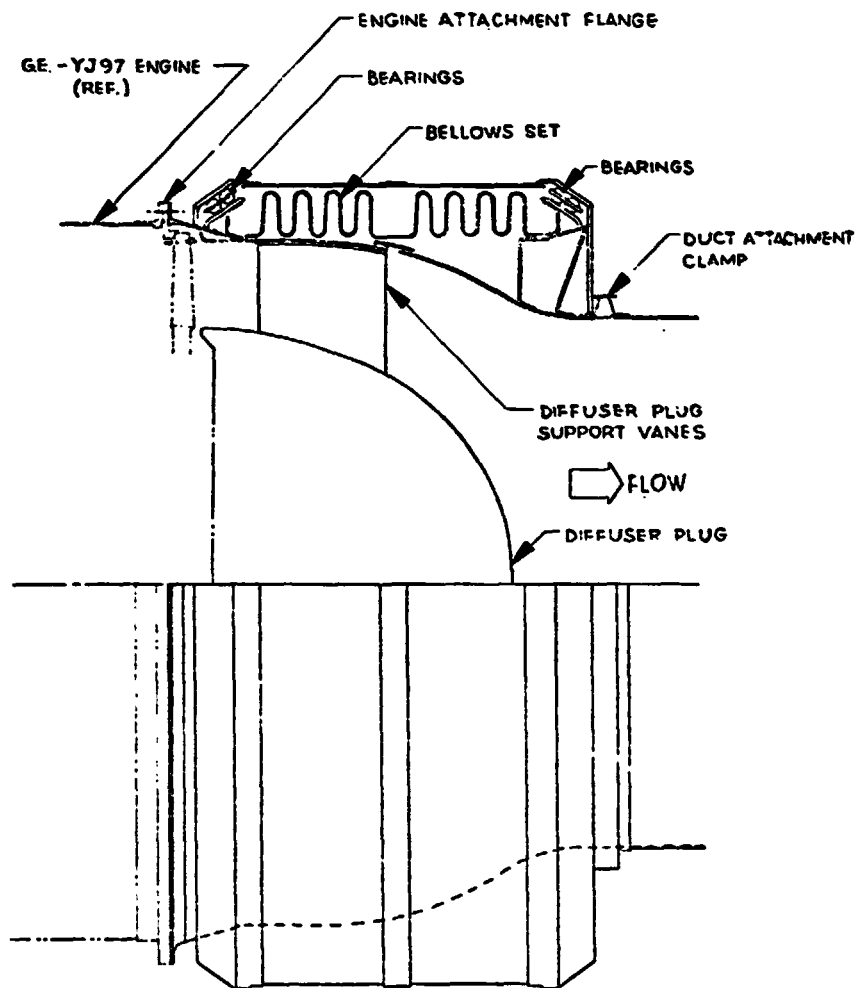
The engine diffuser section, Figure 13, consists of the following items:

- (a) A diffuser plug
- (b) A diffuser fairing
- (c) Antiswirl vane supports
- (d) Two ball bearing assemblies
- (e) An articulated bellows set assembly
- (f) Two attaching flanges.

The engine diffuser section serves a twofold purpose in the RTA gas distribution system. First it diffuses the hot gases from the engine turbine exhaust, as in a normal installation, and expands it to fill the 17 in. diameter duct at M_N of 0.30; and second, it prevents the thermal growth of the attached ducting from imposing extraneous bending loads on the engine case.

The diffuser plug is supported by the diffuser fairing through the anti-swirl vanes. The ball bearing assemblies, which allow the complete assembly to rotate and/or translate through small angles as the downstream ducting aligns itself to meet temperature and loading conditions, is sealed against gas leakage by the bellows arrangement shown on the reference drawing. The

FIGURE 13
ENGINE DIFFUSER AND ALIGNMENT BEARING SECTION



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pressure piston load in the bellows is reacted by the cylindrical shell supporting the outer races of the bearings keeping the component in equilibrium.

1.6 COMPONENT MATERIALS SELECTION

The maximum duct system operating temperature of 1375°F and normal operating temperature of 1260°F makes available a variety of materials which have the required characteristics of superior corrosion resistance, resistance to creep, high stress rupture strength, and superior oxidation resistance. These service temperatures are more significant with respect to long term metallurgical stability since this is in the range conducive to carbide precipitation and the formation of brittle intermetallic phases. A number of available superalloys were screened as possible component materials, including the following:

21-6-9	Inconel X-750
N-155 (Multimet)	Inconel 718
Inconel 600	Hastelloy X
Inconel 601	Haynes 188
Rene' 41	Inconel 625
Inconel 718	Inconel 617
	L-605

The austenitic 21-6-9 is one of the new stainless steels offering better strength than the 18-8 class. Its oxidation resistance is more than adequate for the application; but even with its low carbon content, there is a tendency for carbides to precipitate with long time exposure at the service temperature. This behavior would result in reduced intergranular corrosion resistance and ductility. Typically, 21-6-9 is used in a cold worked condition for improved strength; and since welding reduces the local area to annealed properties, the alloy is not competitive for welded applications. Since this application requires welding, 21-6-9 offers little advantage over the 18-8 stainless steel grades. For these reasons, 21-6-9 was not attractive for this application.

N-155 is one of the oldest superalloys and contains roughly 20% each of chromium, nickel and cobalt. It has excellent oxidation resistance well above the service temperatures, but its high carbon content raises the question of intergranular corrosion resistance and ductility after long time elevated temperature exposure. While it would probably perform satisfactorily in this application, it is not judged competitive with the other candidate materials.

Inconel 600 and 601 exhibit superior oxidation resistance to temperatures above 2000°F, but they have low strength. Typical applications for these alloys

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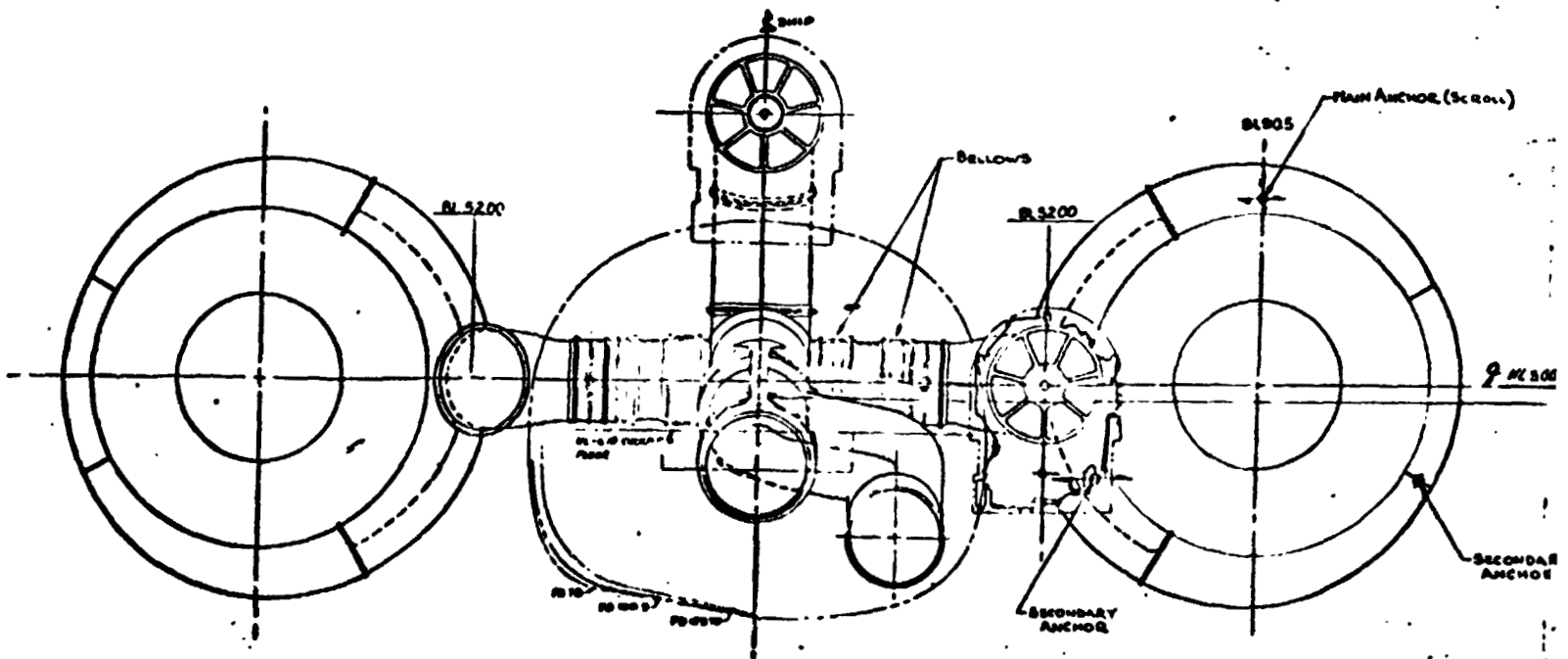
are therefore nonstructural, such as heat-treating baskets, fixtures and furnace components. They both would be more than adequate for the application in terms of oxidation resistance and metallurgical stability, but they would not be weight competitive with the other higher strength candidate alloys.

The remaining alloys can be divided into two classes: those which are strengthened through precipitation heat treatment and those that are solid solution strengthened.

The precipitation hardening alloys included Rene' 41, Inconel 718, and Inconel X-750 but the higher strength they offer is offset somewhat by the difficulty experienced in fabrication. The aging treatment required after fabrication creates a distortion problem which is related to the complexity of the formed part. For simple parts, use of these alloys may be feasible; for most complex parts, the increased fabrication costs will make their use impractical. As with the previous alloys, these exhibit more than adequate oxidation resistance and metallurgical stability for the RTA application. The service temperature, 1260°F, approximately represents the limit for long term exposure of Inconel 718.

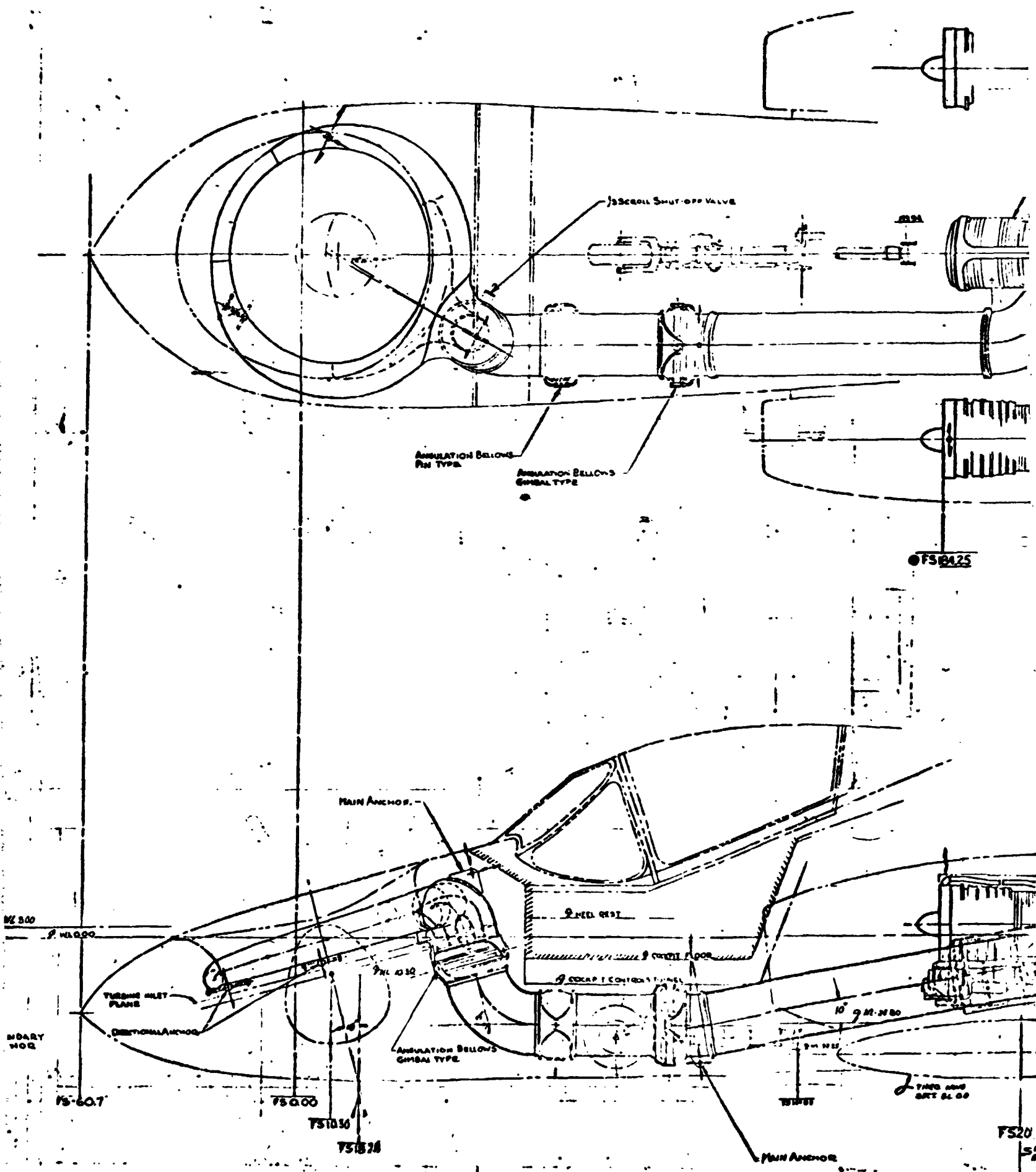
The solid solution strengthened alloys are much easier to fabricate into complex structures, because they require no thermal treatment after forming or welding. The alloys in this category include Hastelloy X, Haynes 188, Inconel 625, Inconel 617, and L-605. Any of these alloys, all of which are readily available, will function satisfactorily in the system environment.

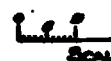
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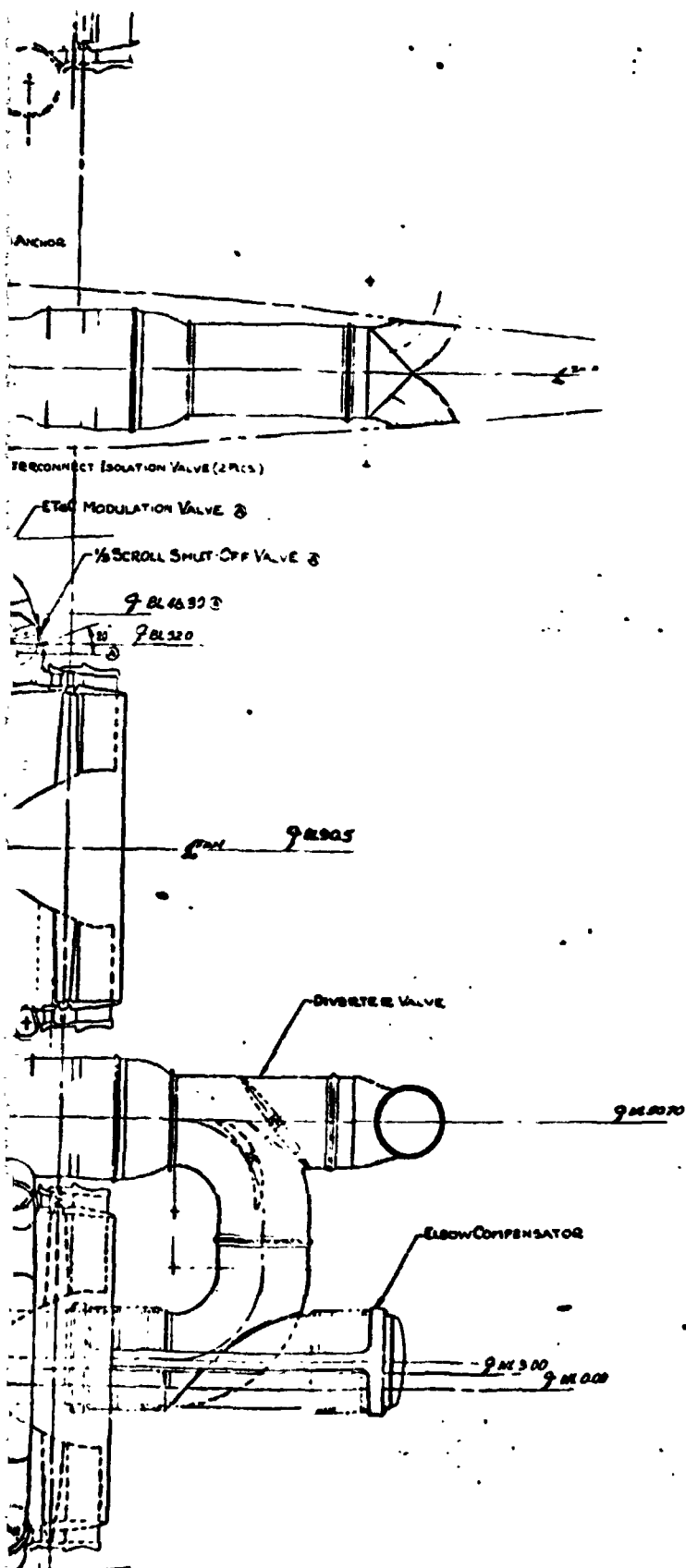


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FOLDOUT FRAME







CONNECT - (100 SPSH)
 LAD-OUT CHARGE SCROLL ENTRY
 LAD-OUT CHARGE ALIGNMENT BAR ASSY
 LAD-OUT CHARGE ENGINE FACE LOCATION FROM
 P3 10000 TO P3 10005

REVISION	DESCRIPTION
1	RTA ENGINE/FAN GAS DIST SYSTEM VARIABLE AREA SCROLL - STUDY NO. 3
2	RTA 260-001-4
3	
4	
5	
6	
7	
8	
9	
10	

4. LIFT/CRUISE FAN THRUST VECTORING DEVICES

2.1 GENERAL DESCRIPTION

The thrust vectoring devices used for the lift/cruise fans were selected for evaluation to determine the feasibility of the basic design concept in regard to state-of-the-art fabrication techniques. The thrust vectoring elements consist of an inner and an outer hood and a set of yaw doors. The hoods are stowed during aerodynamic flight and are rotated into the fan air stream during powered lift flight for thrust deflection. The yaw doors are closed during aerodynamic flight and form the floor of the exhaust nozzle. During powered lift flight, the doors are opened and by deflection into the fan air stream produce yaw moments for the aircraft. The estimated temperatures expected on these elements are shown in Figure 14 and are based on the 36 inch thrust vector nozzle tests recently completed at NASA Ames Research Center. The basic design concepts for the hoods and yaw doors were coordinated with the Astech Company to assure that state-of-the-art fabrication procedures can be used.

2.2 THRUST VECTORING HOODS

These dual rotating hood segments provide for the lift/cruise fan thrust deflection during all modes of aircraft powered lift flight. The inner and outer hoods rotate independently of each other and can be moved from a 0° vector position (cruise) to -105° vector position (vertical). The design concept of the hoods provides for shielding from the exhaust gas temperature during cruise flight. The internal hood pressure and exhaust gas temperature, which impinge on the hoods during vectoring, are low enough to allow the construction materials to be either 2219-T87 aluminum honeycomb or polyamide graphite sandwich. The aluminum was selected for this application.

The inner hood canopy rotates about the fixed nozzle and the outer hood rotates about the inner hood. The hoods are 1-1/8 inch uniform thickness. Guide rollers are used between the hood segments to control the clearance. Seals are provided between the outer hood and the fixed nozzle and between the inner and outer hoods. The pivot fitting for both hoods is an aluminum machining which is bonded into the honeycomb sandwich. A lug projecting from the side of the pivot fitting is used as the attachment point for the hood drive link. The inner and outer hoods are illustrated in Figure 15. State-of-the-art fabrication methods are used.

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FIGURE 14
"D" VENTED NOZZLE
WALL TEMPERATURE MEASUREMENTS
112° GEOMETRIC POSITION
84° VECTOR ANGLE $N_F/\sqrt{\theta} = 95\%$

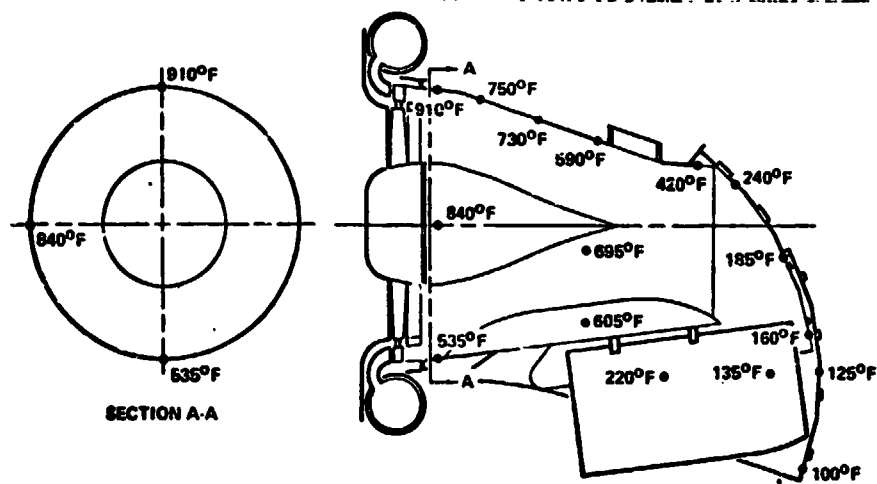
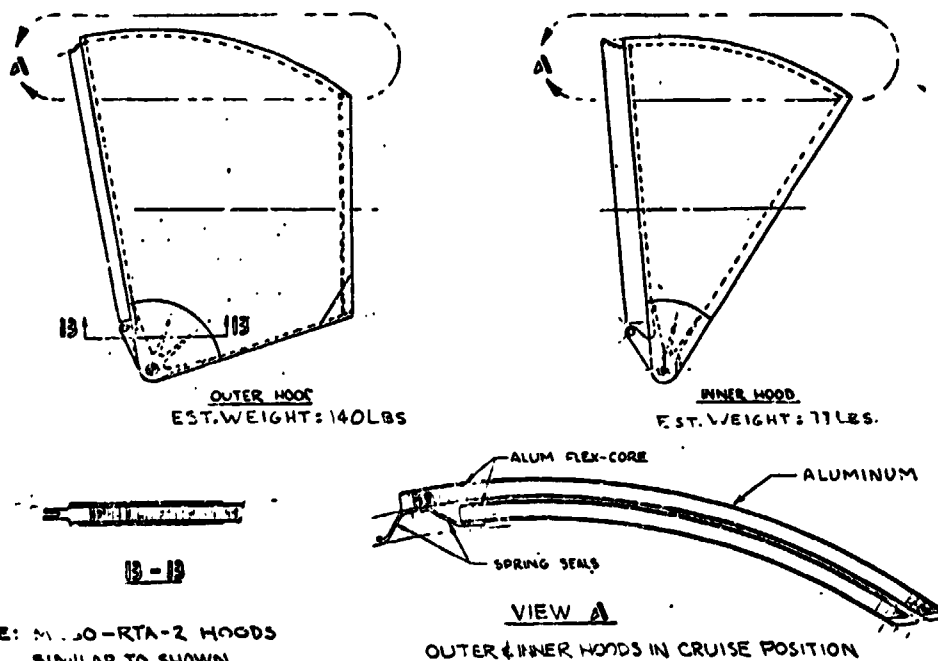


FIGURE 15
M260-RTA-1
LIFT/CRUISE FAN HOOD DESIGN



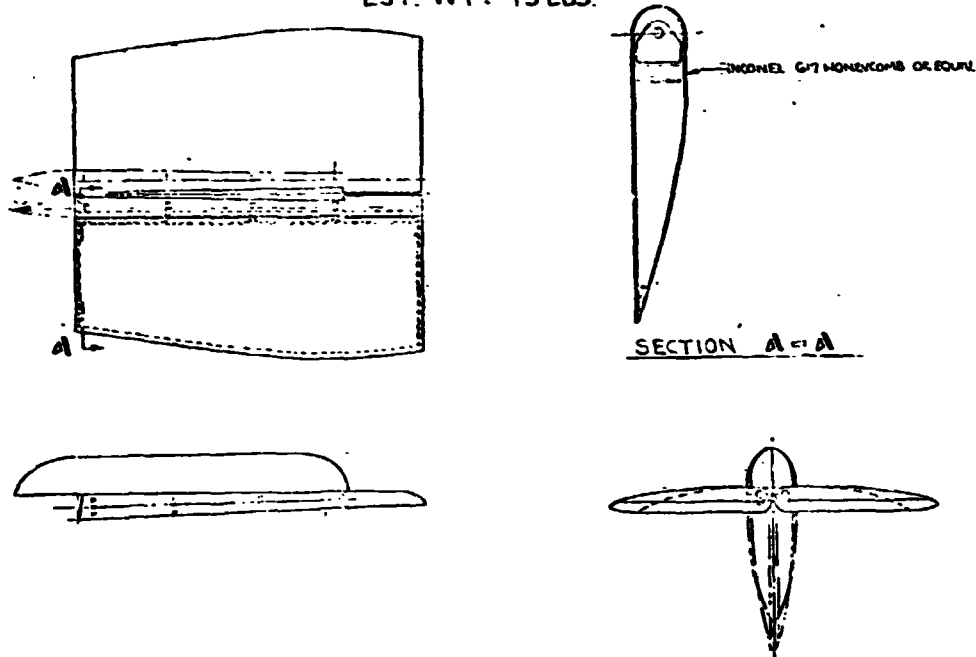
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2.3 YAW DOORS

The yaw doors function both as closure doors during cruise flight and as yaw moment producing devices in powered lift flight. Since the doors are exposed to the high exhaust gas temperature during cruise flight, Inconel 617 or equivalent was selected as the construction material. Seals are provided on the fixed interface structure: hinge plane, forward lip and exit nozzle. State-of-the-art fabrication procedures are employed. The yaw doors are illustrated in Figure 16.

FIGURE 16
M260-RTA-1
LIFT/CRUISE FAN YAW DOOR DESIGN
EST. WT: 75 LBS.



NOTE: M260-RTA-2 YAW DOORS SIMILAR TO SHOWN

3. MECHANICAL TRANSMISSION SYSTEM

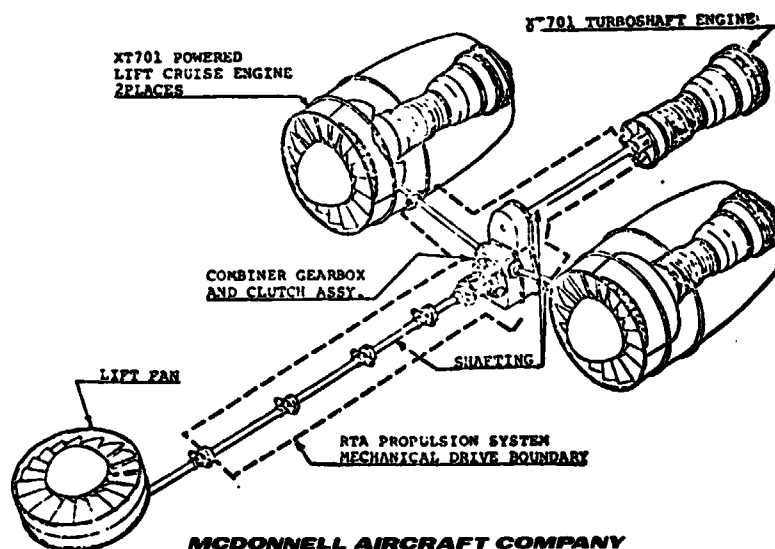
3.1 GENERAL DESCRIPTION

The propulsion system is composed of three Allison XT701 engines driving three Hamilton Standard variable pitch fans. The engines and fans are interconnected by a mechanical transmission system shown in Figure 17, and consists of shafting, combiner gearbox and forward fan clutch.

The lift/cruise fan assemblies (two) are located above the wing and adjacent to the fuselage. The engine, mounted directly behind the fan, is integrated into the lift/cruise nacelle. Fan supercharged air is inducted into the engine and exhausted together with the fan by-pass air through the thrust vectoring nozzle. Lift/cruise fan speed is reduced below free turbine speed by a planetary gear set. An overrunning clutch installed ahead of the engine between the engine and the planetary set permits overrunning in the event of an engine failure. The Allison XT701 engine is coupled with a Hamilton Standard variable pitch fan to form the compound turbofan/shaft engine unit identified as the Allison PD370-25A. The fan assembly includes a spiral bevel gear set to transmit power to the other two fans for control power, or power transmission during an engine out condition.

The Hamilton Standard variable pitch lift fan is located forward of the cockpit. The fan assembly includes a spiral bevel gear set to transmit power to the fan from the forward drive shaft. Power is transmitted from the combiner gearbox to the lift fan through a wet disk clutch to provide for disengagement

FIGURE 17
MODEL 260-RTA-2
PROPULSION SYSTEM



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of the fan during ground operation, if desired, or in the cruise mode.

The third engine (center) drives into the combiner gearbox through a spur gear set into the transmission system. The combiner gearbox also accepts power from the two lift/cruise engines for distribution during control excursions and engine out operation.

3.2 TRANSMISSION SYSTEM DESIGN

The expertise and experience of Detroit Diesel Allison (DDA) in power transmission systems was employed in the study of the design, development and estimating of the RTA mechanical transmission system with a subcontract arrangement. The work to be performed under the contract was defined in MCAIR Work Statement WS-SDPS-960. The ground rules established by MCAIR for the contracted study are defined below:

- (a) Power Requirements - The system was sized for an aircraft requiring a normal total thrust of 28,275 pounds and an engine out thrust of 25,740 pounds.
- (b) Control Margin - The control margins specified were 27% at normal (3 engine operation) power and 13% during engine out.
- (c) Duty Cycle - The operational duty cycle to which DDA designed the system is defined below:
 - 40% of time at normal standard T.O. power
 - 30% of time at high cruise power (75%)
 - 20% of time at normal cruise power (60%)
 - 10% of time at idle power.
- (d) Gear Design - The gears in the transmission system were designed for infinitive life at normal power plus full control.

Under the terms of the subcontract, DDA supplied design data for a power transmission system which, per agreement with MCAIR, emphasized a low cost, low risk design and did not include excessively low weight advanced technology. The component weights which resulted from this study are as follows:

Component	Weight (lb)
Combiner Box Assy. (including clutch)	412.8
Cross Shafts (including support bearings)	19.4
Center Engine Shaft	15.7
Fan Shaft (including support bearings)	98.2
Total	546.1

Complete results of the DDA effort in response to the MCAIR work statement are presented in Appendix A.

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APPENDIX A

MCDONNELL AIRCRAFT COMPANY V/STOL RTA
SHAFT AND TRANSMISSION DESIGN STUDY

By

DETROIT DIESEL ALLISON

MDC A4551
Volume II



Detroit Diesel Allison
Division of General Motors Corporation
Indianapolis, Indiana 46206

**MC DONNELL AIRCRAFT COMPANY V/STOL RTA SHAFT
AND TRANSMISSION SYSTEM DESIGN
STUDY**

EDR 8976

Part I

November 1976



Detroit Diesel Allison
Division of General Motors Corporation
Indianapolis, Indiana 46206

1.0 Introduction

This report was prepared in response to McDonnell Aircraft Co. (MCAIR) Purchase Order Z60C91 wherein Detroit Diesel Allison (DDA) was to conduct a propulsion system mechanical transmission study for the V/STOL-Research and Technology Aircraft (RTA). The complete written response by DDA includes this report (Part 1) and Part 2 covering estimated costs of a shaft system development program.

The effort described herein was accomplished during the period July-August 1976 under the DDA Project Number E76030.

The RTA V/STOL aircraft incorporates a propulsion system as shown in Figure 1.1.

This study has as its objectives the identification of technical risks and preparation of estimates for design, fabrication and testing of assemblies and components for a research and technology aircraft propulsion system mechanical transmission. The components to be covered are those shown in Figure 1.1 and identified as combiner box and clutch and the four shafts leading to the combiner box.

2.0 Design Study

A design study was conducted to define a shafting system in the detail adequate to identify technical risks and estimate costs for design, fabrication and testing. This design study is defined herein.

2.1 Power and Speed Requirements

Prior to the actual shafting system design effort, it was necessary to obtain estimates for RTA system powers and speeds. This effort was conducted at DDA making use of the known data for a Hamilton Standard 62" variable-pitch fan and the DDA XT701 engine. The starting point for this effort was the required thrust and control thrust margin established by MCAIR

- o Total Thrust Required (normal) 28,275 lbs. (margin 22%)
- o Total Thrust Required (1 engine out) 25,740 lbs. (margin 10%)

These thrust levels are to be achieved on 90°F day at sea level static conditions. It was assumed for the purpose of this study that the engines would be flat rated below 90°F and that shaft horsepower would therefore not exceed those determined for the stated conditions.

Performance calculations were made for the RTA system for V.T.O. operation with three engines operational and with an outboard engine out.



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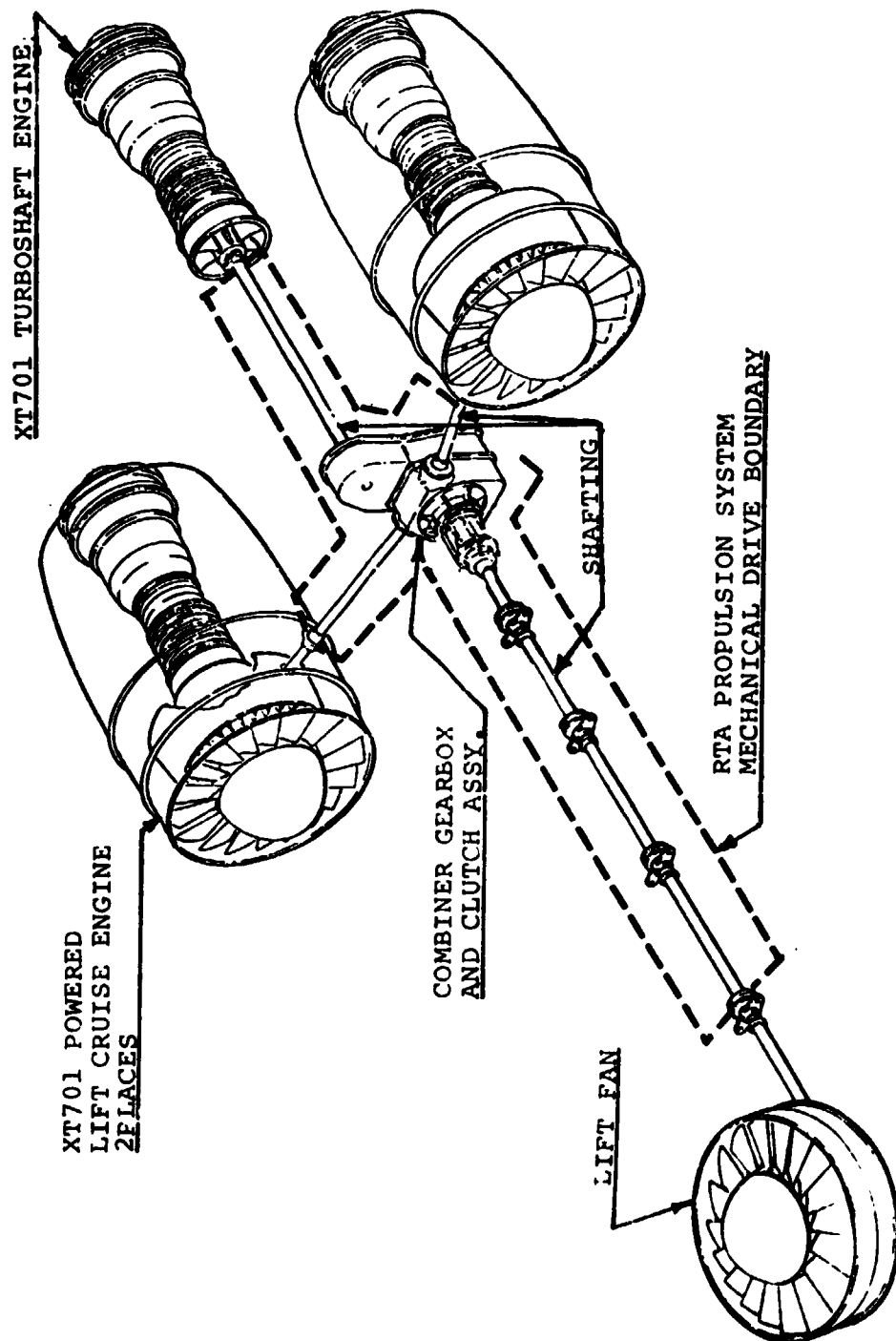


FIGURE 1.1 - RTA PROPULSION SYSTEM



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These calculations were then extrapolated to the nine conditions shown in Table 2.1 and shaft horsepower was determined for each component in the shafting system.

Actual mechanical design speeds for the RTA to be used in this study were established in the following manner.

1. The 100% mechanical fan speed was set at 3,543 RPM.
2. The reduction gear for the lift/cruise engines was assumed to be the T56 planetary set with a ratio of 10:3. This established the 100% lift cruise power turbine speed at 11,810 RPM.
3. Cross shafting from the lift/cruise engines to the combiner box was set close to power turbine speed - 11,805 RPM.
4. The input speed to the lift fan gear box was determined to be 8,432 RPM based on the lift fan gearbox ratio of 2.38:1 established in earlier studies and coordinated with Hamilton-Standard and McDonnell-Douglas.

Figure 2.2 is a schematic showing the RTA power system speeds (100% design point) for each point in the system.

Although other speeds could have been selected for each component in this study, it is believed that the overall results would be the same relative to conclusions on costs, risk and development time.

2.2 Combiner Gearbox Design

2.2.1 General Arrangement and Function

The combiner box transfers power from three engines to the three fans during the powered lift mode. During conventional flight the lift fan is disengaged by the combiner box clutch; the combiner box clutch accelerates the lift fan to operating speed prior to powered lift off and during transition from conventional flight to the powered lift mode.

The center engine input to the combiner box is through a set of helical gears with a 1.4:1 reduction ratio. (See Figure 2.3.) The output gear of this set mounts directly on the shaft driving forward to the lift fan. Each outboard engine is coupled to the lift fan shaft with a right angle set of spiral bevel gears; reduction ratio of 1.4:1. Here again the output gear is mounted directly on the shaft driving forward to the lift fan. Output from the combiner box to the lift fan is through a disk clutch provided with a mechanical lockup for full power transmission. The combiner box is provided with its own lubrication and cooling system, the oil cooler being the only airframe equipment. Controls for clutch actuation



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TABLE 2.1

SHAFT HORSEPOWER DISTRIBUTION - RTA

	NORMAL V.T.O.			RIGHT ENG. OUT V.T.O.			CENTER ENG. OUT V.T.O.		
	Max. Thrust	Max. Pitch	Max. Roll	Max. Thrust	Max. Pitch	Max. Roll	Max. Thrust	Max. Pitch	Max. Roll
Engine Power, Left	6741	6741	6741	9148	9148	9148	8220	8220	8220
Engine Power, Right	6741	6741	6741	0	0	0	8220	8220	8220
Engine Power, Center	5618	5618	5618	7610	7610	7610	0	0	0
Fan Power, Left	6100	5000	40C3	5206	4668	4129	5206	4668	4212
Fan Power, Right	6100	5000	8197	5523	4984	6600	5206	4668	6200
Fan Power, Center	6400	8600	6400	5523	6600	5523	5523	6600	5523
Left X-Shaft Power	453	1564	2567	3666	4207	4732	2819	3366	3814
Right X-Shaft Power	453	1564	-1644	-5581	-5038	-6663	2819	3366	1836
Center Engine Drive Power	5618	5618	5618	7610	7610	7610	0	0	0
Lift Fan Drive	-6452	-8663	-6452	-5570	-6653	-5570	-5570	-6653	-5570

(-) Power Flow Out of Combiner Box



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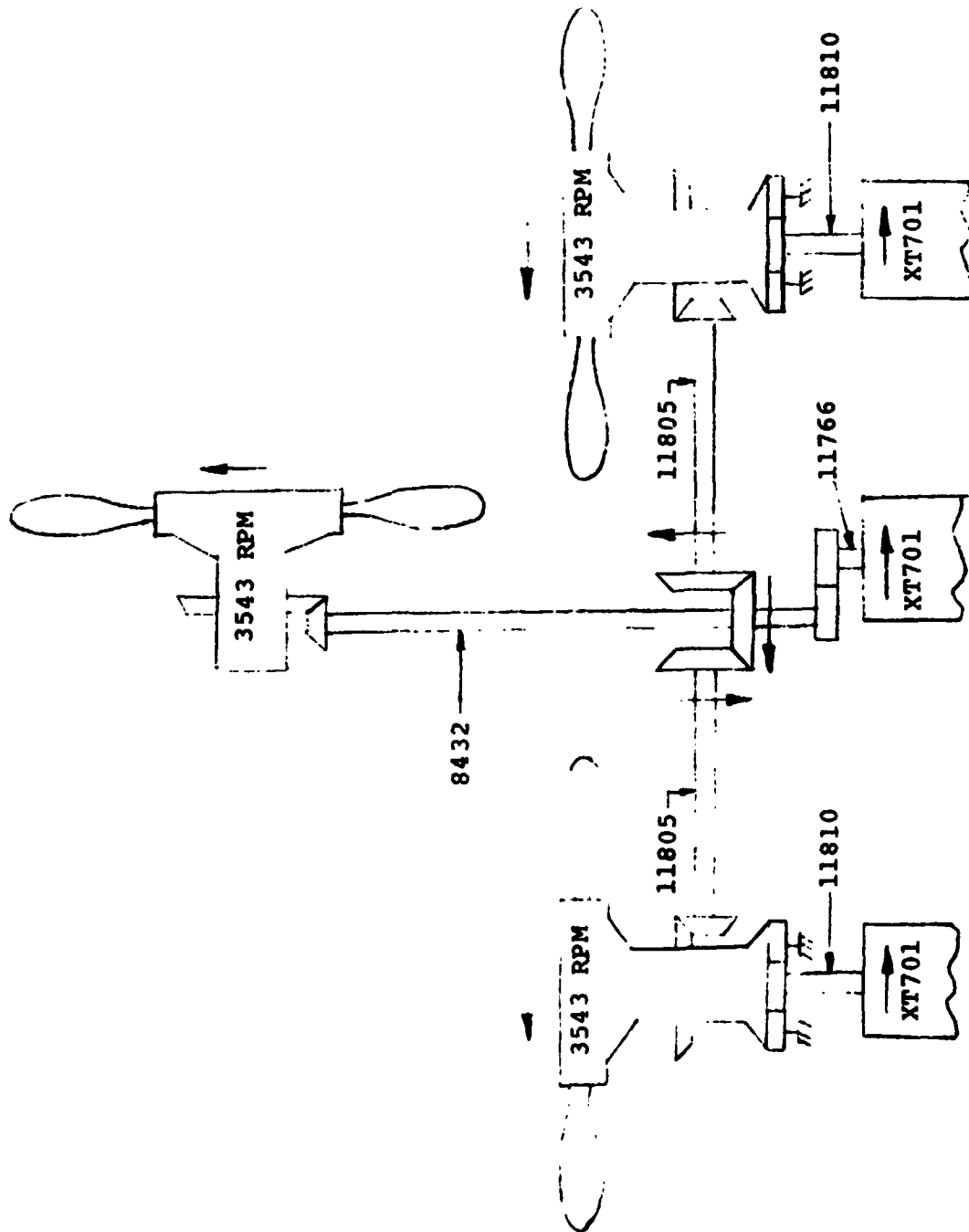


FIGURE 2.2 - RTA POWER SYSTEM DESIGN SPEEDS



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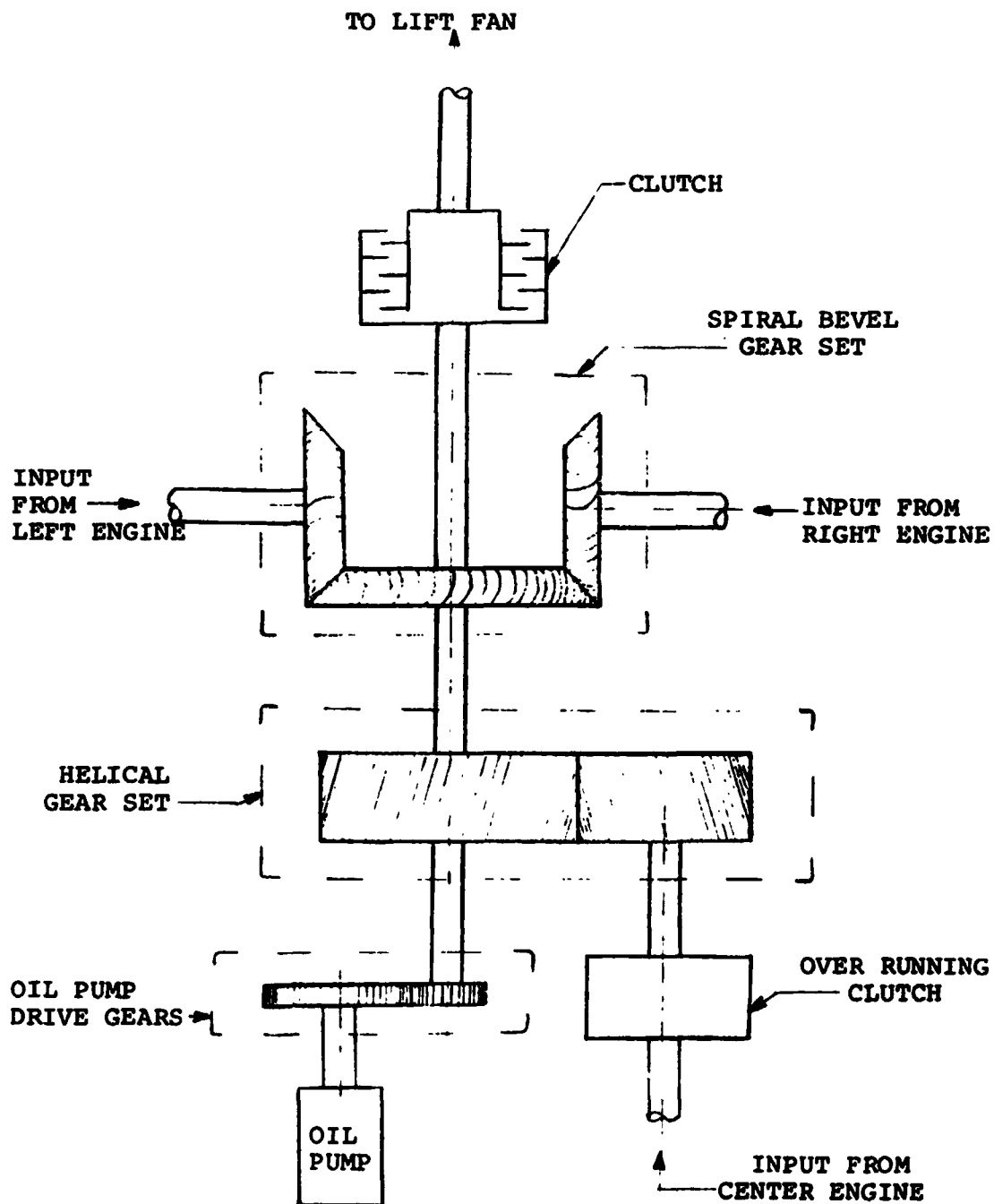


FIGURE 2.3 - COMBINER GEARBOX GEAR SCHEMATIC



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are mounted directly on the combiner box. Figure 2.4 is the combiner box as designed for this study.

2.2.2 Combiner Box Gearing

Spiral Bevel

The spiral bevel gear set was designed to meet the power and speed requirements defined in Section 2.1.

Allowable stress levels were selected to produce infinite life for the spiral bevel gearing. Stresses are calculated according to methods set forth by Gleason Gear Works.

The power levels in Table 2.1 were reviewed to determine the maximum power on the spiral bevel gear set. This was noted to be 6,663 horsepower in the contingency maximum roll mode. Gears are designed to produce infinite life at this condition. This approach affords low risk plus growth for the resultant gear set. (The spiral bevel gears do not have to be inspected after contingency operation.)

Two different gear arrangements were evaluated. The one shown in Figure 2.4 and an alternate arrangement that incorporated an idler bevel gear. The arrangement shown in Figure 2.4 was selected because it offered the most compact, low-weight design for the RTA design power. (It should be noted that higher power levels may not result in the same conclusion.)

Spiral bevel gear calculations were made with a DDA-developed computer analysis that follows from the Gleason methods shown in their publications and used at DDA for some time. The resulting gear set data is shown in Table 2.5 for the design point power level.

Comparisons for stress and pitch line velocity were made with other spiral bevel gear applications calculated in a similar manner. These are shown in Figures 2.6 and 2.7. It can be noted that the RTA design is within the limits of successful earlier designs.

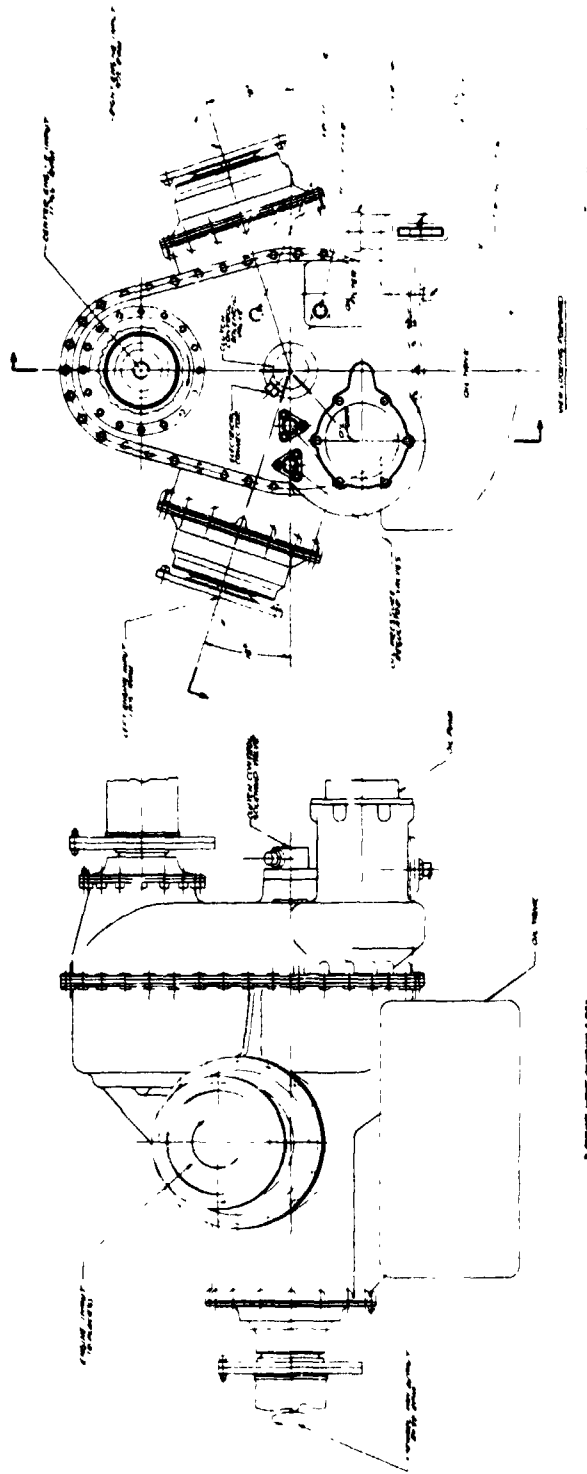


FIGURE 2.4
COMBINER BOX
MDC STUDY-RTA



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TABLE 2.5

COMBINER BOX SPIRAL BEVEL DESIGN DATA

Horsepower-----	6663
Speed (RPM) (Pinion)-----	11805
Shaft Angle-----	90°
Pressure Angle-----	25°
Spiral Angle-----	35°
Diametral Pitch-----	3.089
Bending Stress Pinion (PSI)-----	37900
Bending Stress Gear (PSI)-----	32800
Crushing Stress (PSI)-----	213000
Face Contact Ratio-----	1.72
Pitch line velocity (feet per minute)-----	25000



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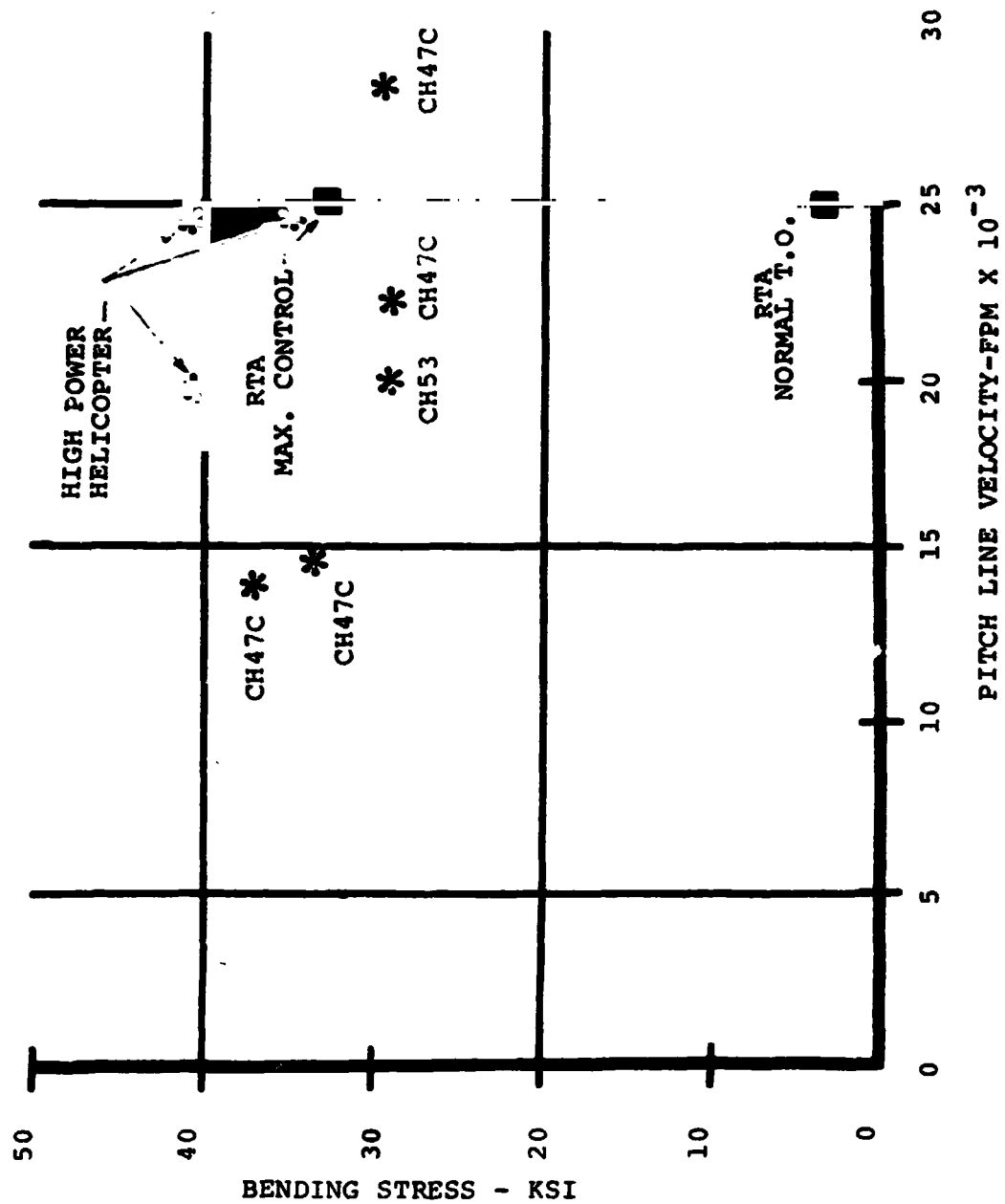


FIGURE 2.6 - RTA SPIRAL BEVEL GEAR COMPARISON WITH PRESENT GEAR SETS



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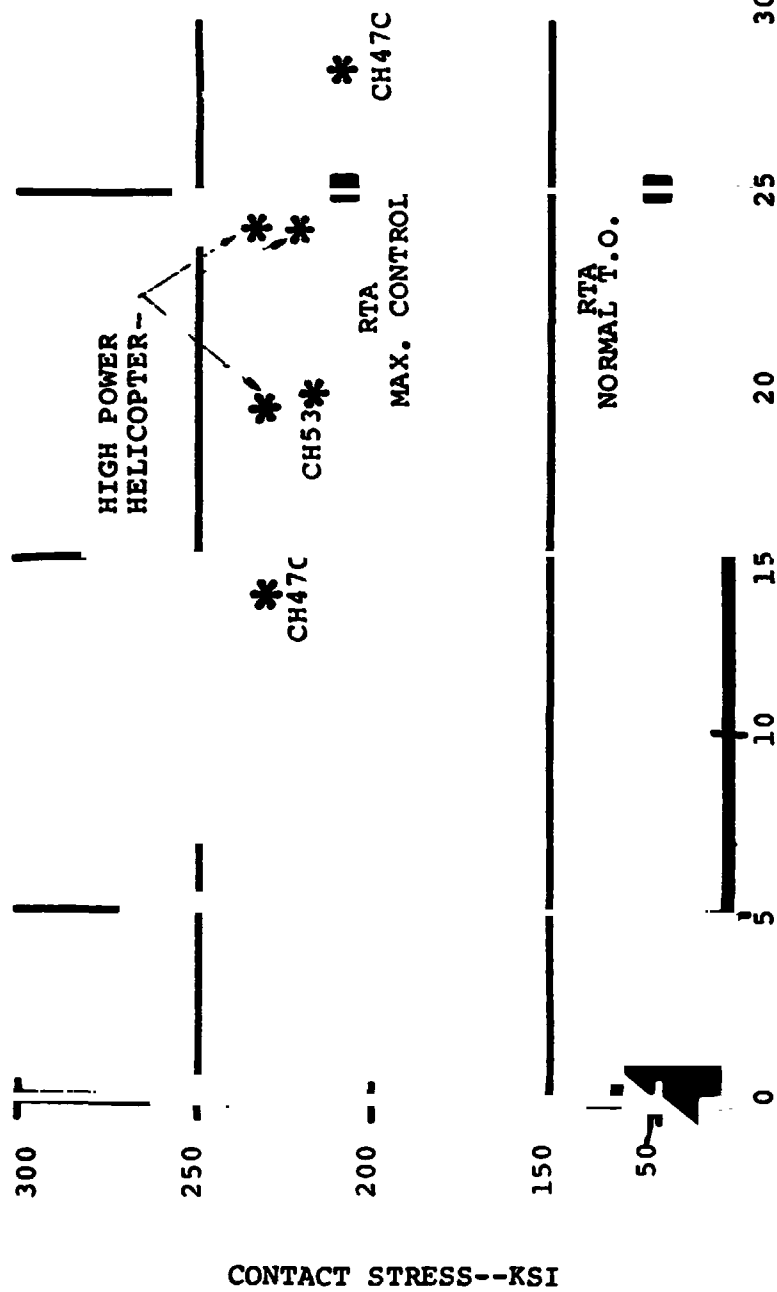


FIGURE 2.7 - RTA SPIRAL BEVEL GEAR COMPARISON WITH PRESENT GEAR SETS



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Helical Gear Set

The helical gear set was designed to provide infinite life at the maximum power levels established in Section 2.1. This is 7610 horsepower.

A DDA-developed computer analysis was used to evaluate numerous helical gear sets and the resulting selection is shown in Table 2.8. Bending stress is calculated with the modified Lewis formula.

Accessory Gears

An accessory gear set is provided to drive the oil pumps for the combiner box. Design goals for this set are the same as noted previously for the helical gear set.

Gear Materials

All the RTA combiner gearboxes are designed of AMS 6265 (CEVM 9310) material which is to be carburized and ground. This gear material has accumulated 64,000,000 flight hours in DDA designed gearboxes and has demonstrated its capability quite satisfactorily.

2.2.3 Bearings

Each bearing position in the combiner box was examined to determine the maximum load for any of the power conditions established in Section 2.1. The minimum bearing static capacity was then required to be no less than the maximum load under any control condition (including contingency). See Figure 2.9 for the location of, and numbering system for, the combiner box bearings.

In order to estimate a fatigue life for each combiner box bearing and for the system, a duty cycle was established by which the mean bearing loads could be evaluated. The duty cycle was biased heavily toward the high power conditions since the RTA is expected to spend a lot of time at high power.

The duty cycle used was:

- o 40% of time at normal standard T.O. power
- o 30% of time at high cruise power (75%)
(3 engines running - lift fan off)
- o 20% of time at normal cruise power (40%)
(3 engines running - lift fan off)
- o 10% of time at idle power



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TABLE 2.8

COMBINER BOX - HELICAL GEAR SET DATA

Horsepower-----	7610
Speed (Pinion)-----	11766
Pressure Angle-----	25°
Helix Angle-----	11.2
Diametral Pitch (Normal)-----	6
Centrifugal Offset (inch)-----	6.75
Face Width (inch)-----	2.8
Pitch Diameter - Pinion (inch)-----	7.3058
Pitch Diameter - Gear (inch)-----	10.1942
Bending Stress - Pinion (psi)-----	30100
Bending Stress - Gear (psi)-----	30100
Crushing Stress (psi)-----	160000
Face Contact Ratio-----	1.04
Pitch Line Velocity (feet per minute)-----	22600



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Bearing fatigue life was calculated based on a modification of the AFBMA method. This procedure includes the effect of material, processing, lubrication, speed and misalignment to produce a more realistic estimate of fatigue life for the actual bearing design and operating conditions.

This procedure was used for the twelve combiner box bearings that are sensitive to transmitted load; for the other six bearings, a combined material and lubrication factor of five was used.

The results of this analysis are shown in Table 2.10.

2.2.4 Lift Fan Clutch

Function

The lift fan clutch is provided to accelerate the lift fan to combiner box output shaft speed. This is accomplished with an oil-actuated, oil-cooled multiple disk clutch. Oil for cooling and actuating the clutch is transmitted to the clutch by tubes passing through the combiner box from a clutch control valve mounted at the rear of the combiner box.

The power requirements for the disk clutch are only those developed by the lift fan while operating at minimum blade pitch plus the inertia for the fan. Those are:

- o *Fan inertia - 475 pound ft²
- o *Fan windage loss - 1000 horsepower at full speed

*Estimates from Hamilton-Standard



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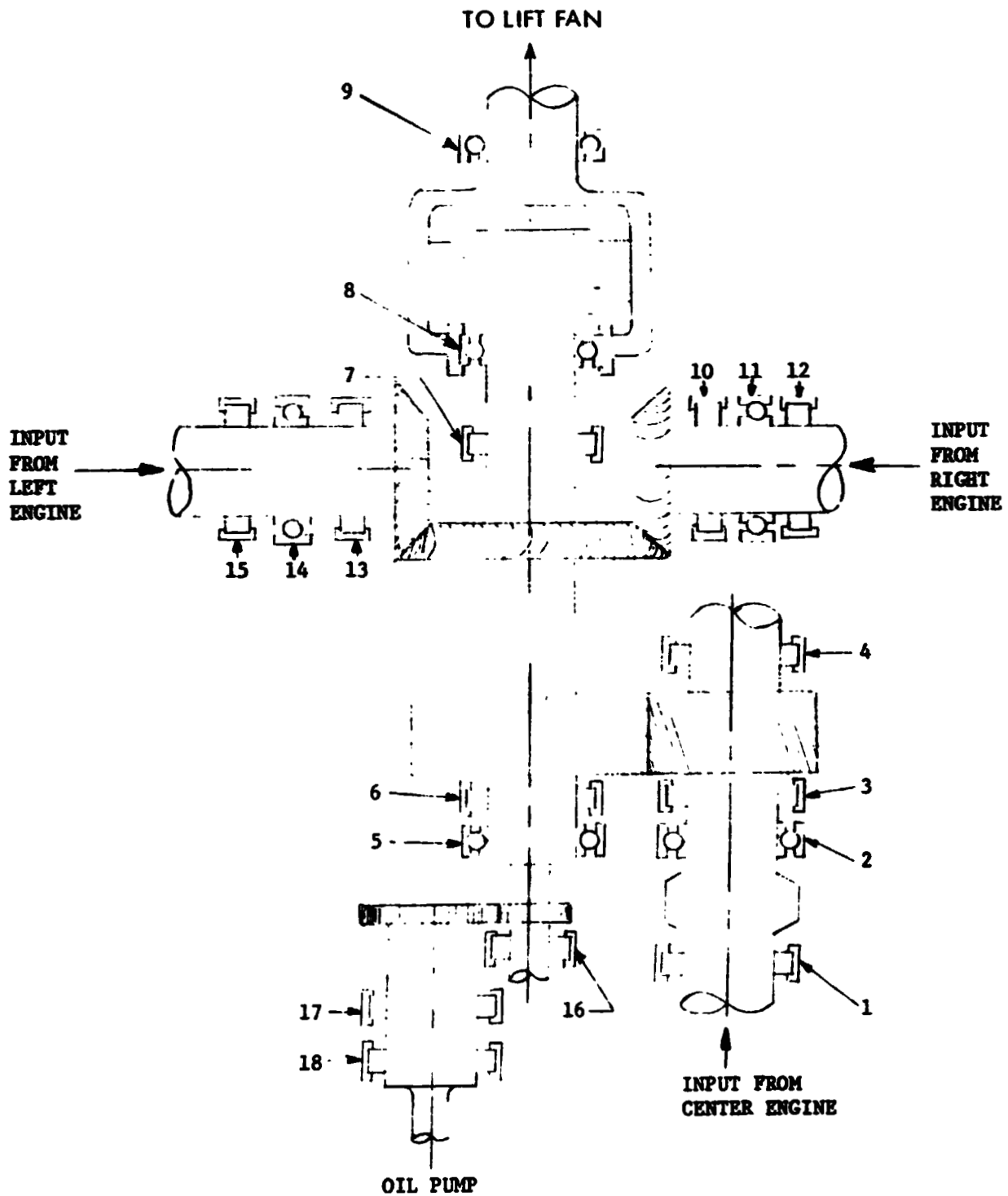


FIGURE 2.9 - COMBINER BOX BEARINGS SCHEMATIC

A-17



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TABLE 2.10 - RTA V/STOL COMBINER BOX BEARING DATA

* CR - Cylindrical Roller; SB - Split Inner Ring Ball

BEARING NUMBER	TYPE*	ENVELOPE B x O.D. x W (mm)	SPEED (RPM)	MEAN LOAD LBS	BI LIFE (HOURS)
1	CR	75 x 105 x 16	11,766	Low	1,000,000+
2	SB	55 x 120 x 29	11,766	1300	5,500
3	CR	55 x 120 x 29	11,766	3500	1,400
4	CR	55 x 120 x 29	11,766	4260	700
5	SB	160 x 220 x 28	8,432	4730	1,250
6	CR	160 x 220 x 28	8,432	5360	750
7	CR	95 x 170 x 32	8,432	2330	16,900
8	SB	100 x 130 x 15	8,432	1100	1,940
9	SB	110 x 140 x 15	8,432	Low	1,000,000+
10	CR	110 x 200 x 38	11,805	5340	2,100
11	SB	110 x 200 x 38	11,805	620	60,900
12	CR	105 x 160 x 26	11,805	2340	1,600
13	CR	110 x 200 x 38	11,805	5340	2,100
14	SB	110 x 200 x 38	11,805	620	60,900
15	CR	105 x 160 x 26	11,805	2340	1,600
16	CR	55 x 80 x 13	8,432	58	1,000,000+
17	CR	35 x 62 x 14	4,577	78	1,000,000+
18	CR	35 x 62 x 14	4,577	20	1,000,000+



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A mechanical lock-up device is provided in the clutch mechanism to permit transmittal of full lift fan power after the disk clutch has brought the fan to combiner box speed. The lock-up device senses disk clutch input and output speed and inhibits lock-up until rotational speeds are matched. Once speeds are matched, lock-up occurs automatically and a signal is generated to the aircraft control system to permit the lift fan blade angle to be advanced in order to develop thrust.

Clutch Disk Materials

The lift fan clutch has been designed to make use of a Teflon based disk facing material recently developed at DDA for a General Motors industrial application. It has shown itself to be quite satisfactory for use at high power loadings while running in industrial transmission oils. For the RTA application, where it is expected that oils per MIL-L-23699 or MIL-L-7808 will be used, it will be necessary to run oil compatibility tests. Data available at this time does not suggest any incompatibilities between aircraft oils and the material but this will be substantiated by test.

Clutch Disk Sizing

The clutch disk size selected for the RTA design is a 7.88 inch diameter plate that is available from other clutch designs on test and in production at DDA. This size yields a 17,400 ft. per minute maximum rubbing speed which is well within the limits of high speed clutches designed by DDA. For example, the T-40 clutch ran at 18,000 ft/minute.

Disk Clutch Details

The clutch as designed for the RTA mission is described as follows:

- o Clutch plate O.D. = 7.88 in.
- o 13 plates - 26 friction surfaces
- o engagement time 6 seconds
- o approximately 1700 BTU total heat rejection



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The previously mentioned clutch development effort at DDA for an industrial clutch provides good guide lines for required clutch coolant flow rate. This is .042 GPM/in² or 24 GPM for the disk clutch. This flow rate is only required during clutch engagement and for approximately 24 seconds following clutch lock-up, at which time the coolant would be turned off.

Clutch piston pressure required to achieve the 6-second engagement time would be approximately 100 psi maximum.

2.2.5 Over-Running Clutch

The over-running clutch was provided at the center engine input to the combiner box to allow for planned or emergency shut down of the center engine.

The clutch as shown in Figure 2.11 is similar to one designed and developed in the T56-A-18 program. Normal power transfer through the clutch is accomplished by a double set of helical splines that do not permit disengagement with a positive torque application. When the center engine is shut down and clutch torque goes negative, the helical splines force disengagement. While running in the disengaged mode, ratcheting of the spline is inhibited by an axially unbalanced centrifugal oil head within the over-running clutch. The clutch design will permit an in-flight start-up of the center engine.

The combiner box over-running clutch is the same basic design as would be used in the lift cruise engine gearboxes.

2.2.6 Lubrication and Cooling System

The combiner box design contains a completely integrated lubrication and cooling system (the oil cooler would be airframe supplied and mounted). Included in the system are the following:

- o Low pressure pump for cooling and lubrication
- o High pressure pump for clutch control and gear lubrication
- o Oil filter
- o Pump regulators
- o Pump and filter relief valves
- o Scavenge pumps
- o Clutch control valve
- o Oil tank (sight glass-filler)

This system is shown schematically in Figure 2.12.



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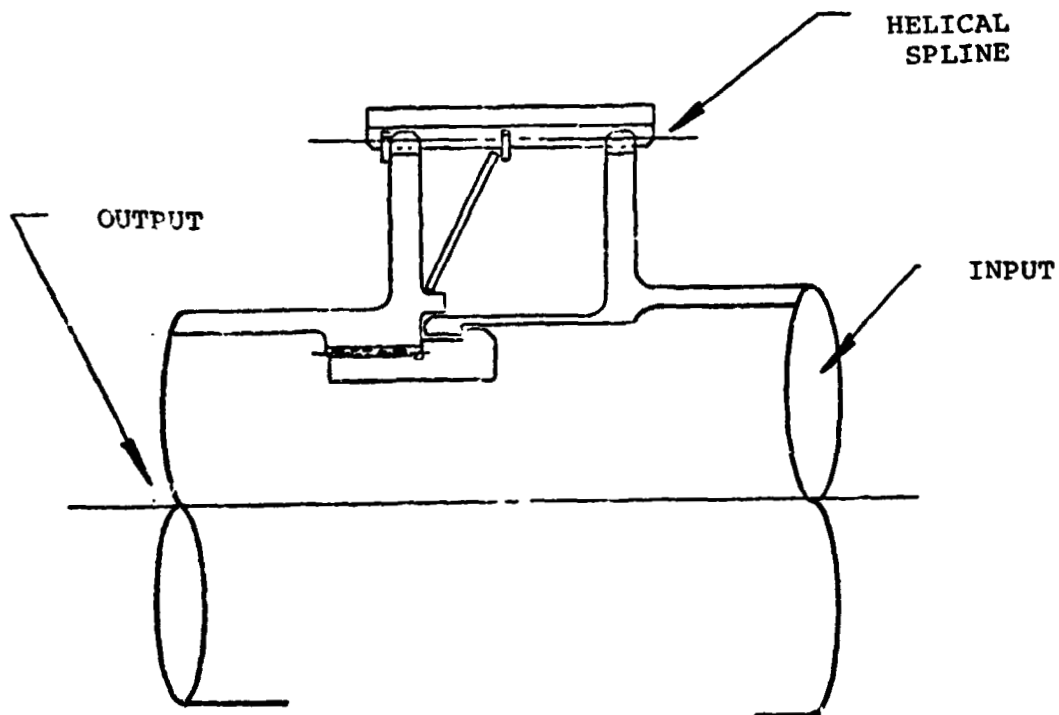


FIGURE 2.11 - OVER-RUNNING CLUTCH



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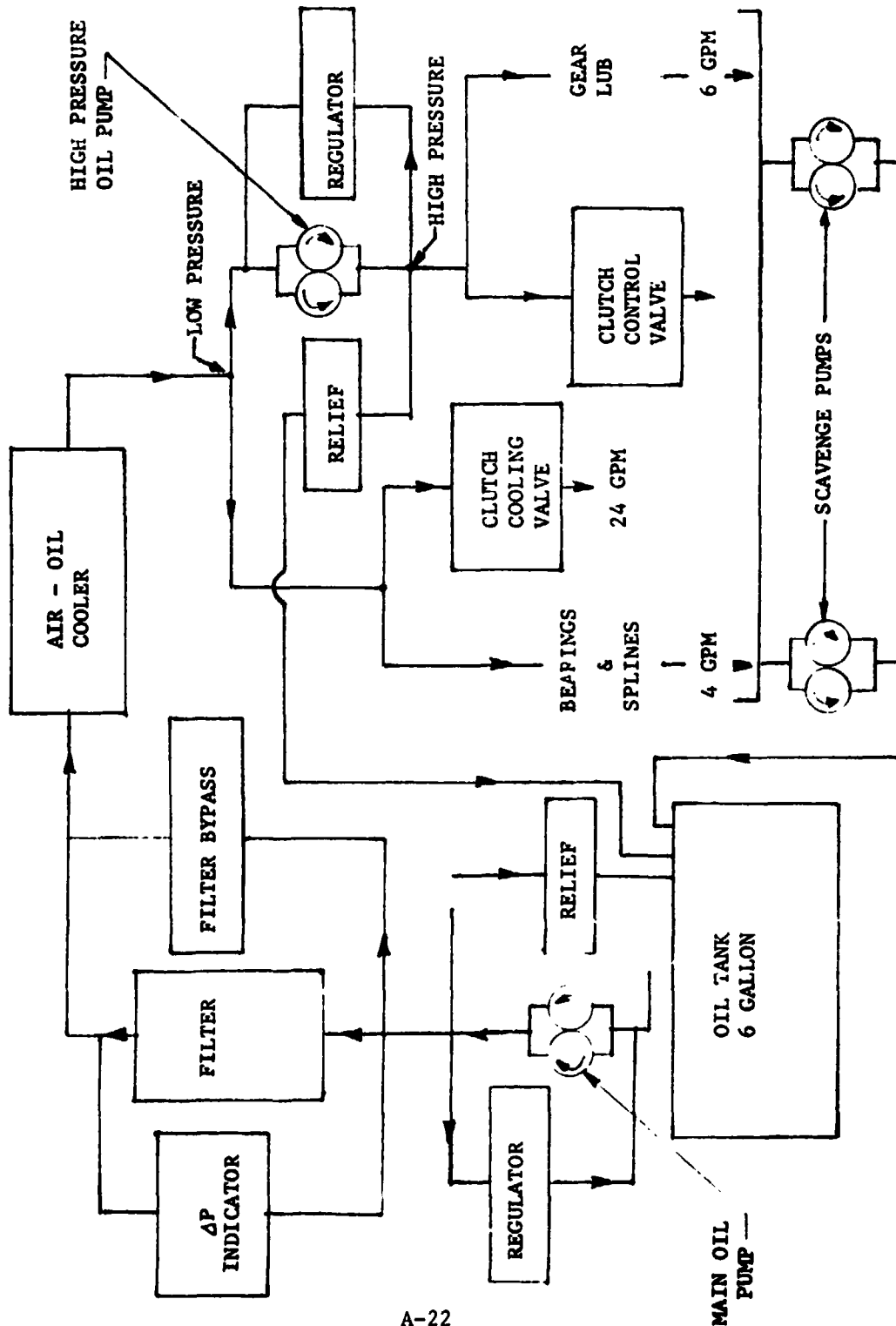


FIGURE 2.12 - OIL SYSTEM SCHEMATIC



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The oil system cooling requirements are estimated in the following manner.

1. Combiner box windage losses at full speed - 1700 BTU/min
2. Gear and bearing system losses (1/2% of power in each gear mesh) at T.O. power (normal) - 1400 BTU/min
3. Gear and bearing system losses at contingency T.O. condition - 3560 BTU/min
4. Clutch heat rejection for each engagement cycle - 1700 BTU

The gearbox cooling system was designed to handle the normal T.O. power heat rejection with a 100°F oil system ⁴¹. This suggests a normal flow rate of 10 GPM through the gearbox at all times except when the clutch is engaged. During clutch engagement and for 24 seconds thereafter an additional 24 GPM is added to the system flow to absorb the clutch heat rejection of 1700 BTU.

An approximation of total heat rejection at the time of clutch engagement is shown in Figure 2.13.

It is suggested that the oil cooler be sized to handle the normal T.O. power heat rejection of 3100 BTU/min and that the clutch heat rejection be treated as a transient, i.e., allow the system temperatures to rise during clutch engagement and dissipate this heat gradually over a period of time. The large thermal mass of the combiner box will keep the peak temperatures within reasonable limits.

Total oil contained in the sump is six gallons. This quantity is necessary to permit deaeration of the oil when the flow rate is 34 GPM.

Oil pumps for the system are conventional spur gear pumps controlled by by-pass regulators and protected by pop-off type relief valves.

2.2.7 Case Structure and Mounts

The main combiner box case structure is made up of three magnesium castings (two covers and a diaphragm). The magnesium would be coated for corrosion protection. Mounting pads are cast integral with the case and could be located to be compatible with the local airframe structure. The oil tank is mounted directly on the combiner box.

2.2.8 Materials

Figure 2.14 shows the various materials that have been selected for components of the combiner box.



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Indianapolis, Indiana 46206

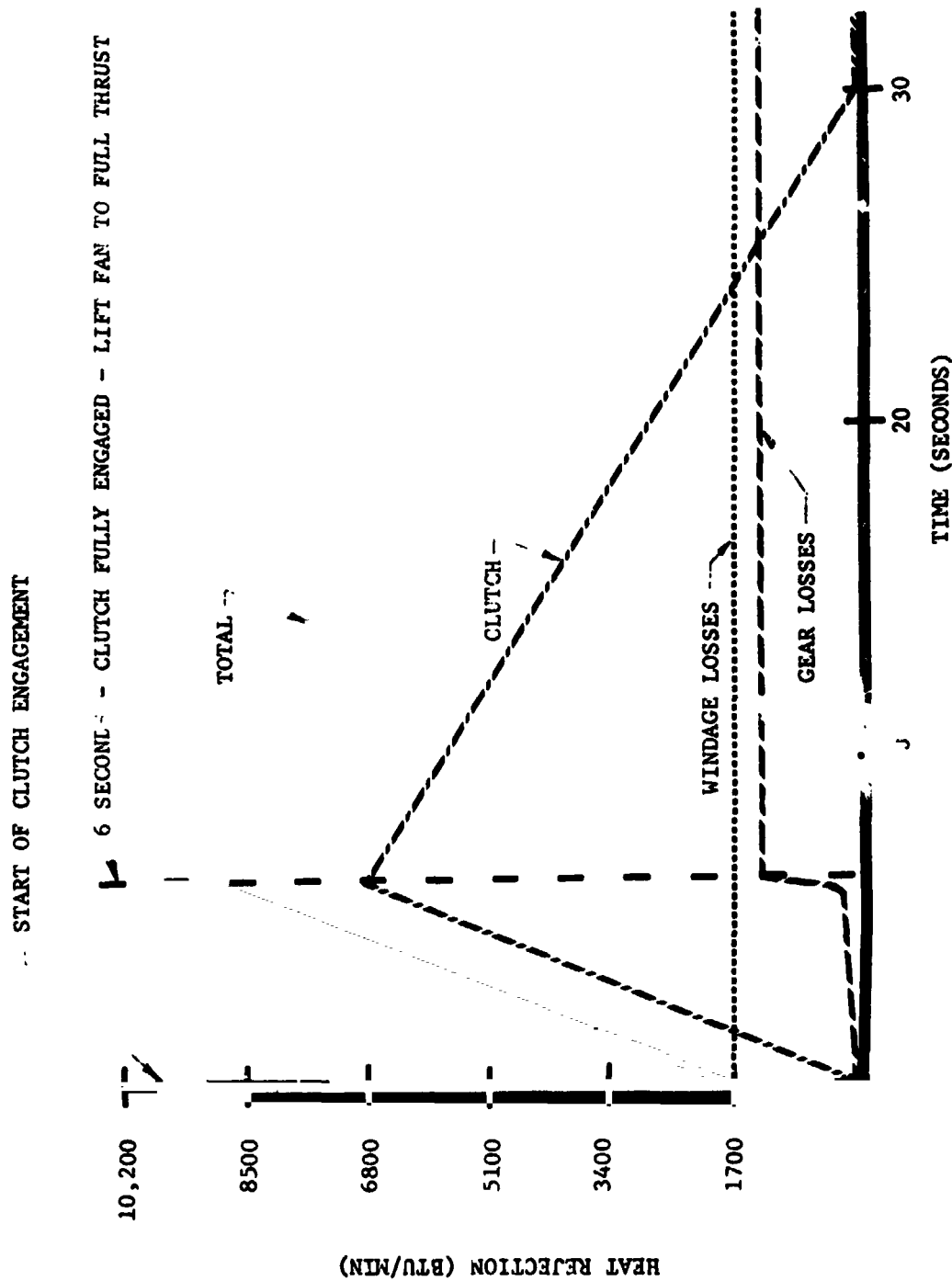


FIGURE 2.13 - PLOT OF HEAT REJECTION DURING CLUTCH ENGAGEMENT



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Table 2.14 RTA V/STOL PROPULSION SYSTEM

MECHANICAL DRIVE MATERIALS TABULATION

Shafting

Shaft	AMS5512
Support Bearings	SAF52100
Damper	Rubber
Couplings	AMS6512
Seal Plates	AMS5504
Housing	AMS5350

Combiner Box

Housings	AMS4434
Shafting	AMS64500 Steel
Gears	AMS6265
Bearings	AMS6444
Oil Tank	AMS5646
Clutch Input-Output	AMS6415
Clutch Plates	AMS6355
Seals	Carbon
Fasteners	A-286
Brackets, Plates	AMS6415
Spanner Nuts	AMS6415



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2.3 Shafting

The shafting for the RTA propulsion system was designed to meet the speed and load requirements established in Section 2.1. Subcritical design points were selected to minimize development effort and risk. (The weight increase for this approach is slight.) Figure 2.15 is the RTA shaft system.

Shaft design details are shown in Table 2.16.

Critical speeds were calculated for each shaft assuming simple supports. The lift fan shaft was evaluated for a number of different segments and it was found that the minimum weight for the shaft (including intermediate support bearings) was achieved with four sections of shafting. It should be noted that the lift fan shaft discussed herein does not include the portion of the shaft that passes through the lift fan air stream strut.

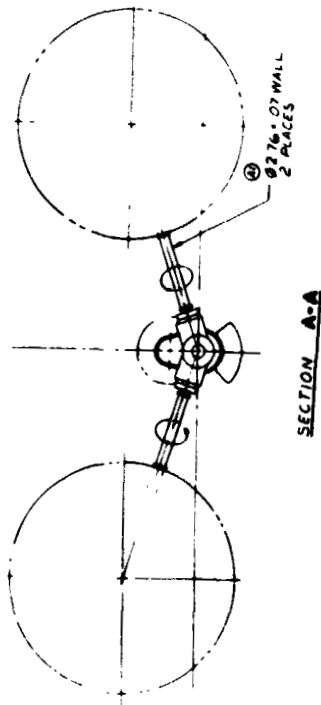
A support bearing and coupling assembly was designed for use at each intermediate point of support for the lift fan shaft. See Figure 2.17. The support bearings are lubricated by grease that is circulated through the bearing by a built-in viscous pump. Bearing loads are low for the shafting and there are not any rubbing grease seals to wear out, therefore this type of assembly is expected to give a long trouble-free life. Routine maintenance would not be required of this assembly.

The coupling incorporates a diaphragm to allow for shaft angular misalignment and limited axial displacement. The number of diaphragms in the coupling can be varied to account for misalignment. Airframe attach points for the lift fan support bearings would not require precise machining tolerances, rather it is planned that the supports would be shimmed to fit at installation.

A reasonable control on the combiner gearbox to lift fan distance would be expected and the tolerance for this would be taken up in the end fittings at assembly.

Each lift fan shaft coupling assembly is estimated to weigh 12 pounds.

Shafting materials are shown in Figure 2.14.



102° REF

3°

Ø 4.20 - .07 WALL & PLACES

Ø 4.20 - .07 WALL

STA 6.28

STA 7.01



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TABLE 2.16

	SHAFT DESIGN DETAILS		
	CROSS SHAFT	CENTER ENGINE DRIVE SHAFT	LIFT FAN DRIVE SHAFT
TOTAL SHAFT LENGTH (in.)	23.5	42	194.4
NUMBER OF SECTIONS	1	1	4
SECTION LENGTH (in.)	23.5	42	48.6
MAXIMUM POWER (HP)	6663	7610	8663
SPEED at MAXIMUM POWER (%)	100	100	100
DESIGN SPEED (RPM)	14805	11766	8432
DESIGN TORQUE (in-lb)	46244	52992	84177
SHEAR STRESS PSI	59600	26114	45630
MINIMUM SPEED FOR CRITICAL	16527	16472	11805
SHAFT O.D. (in.)	2.76	4.4	4.2
SHAFT WALL (in.)	.070	.070	.070



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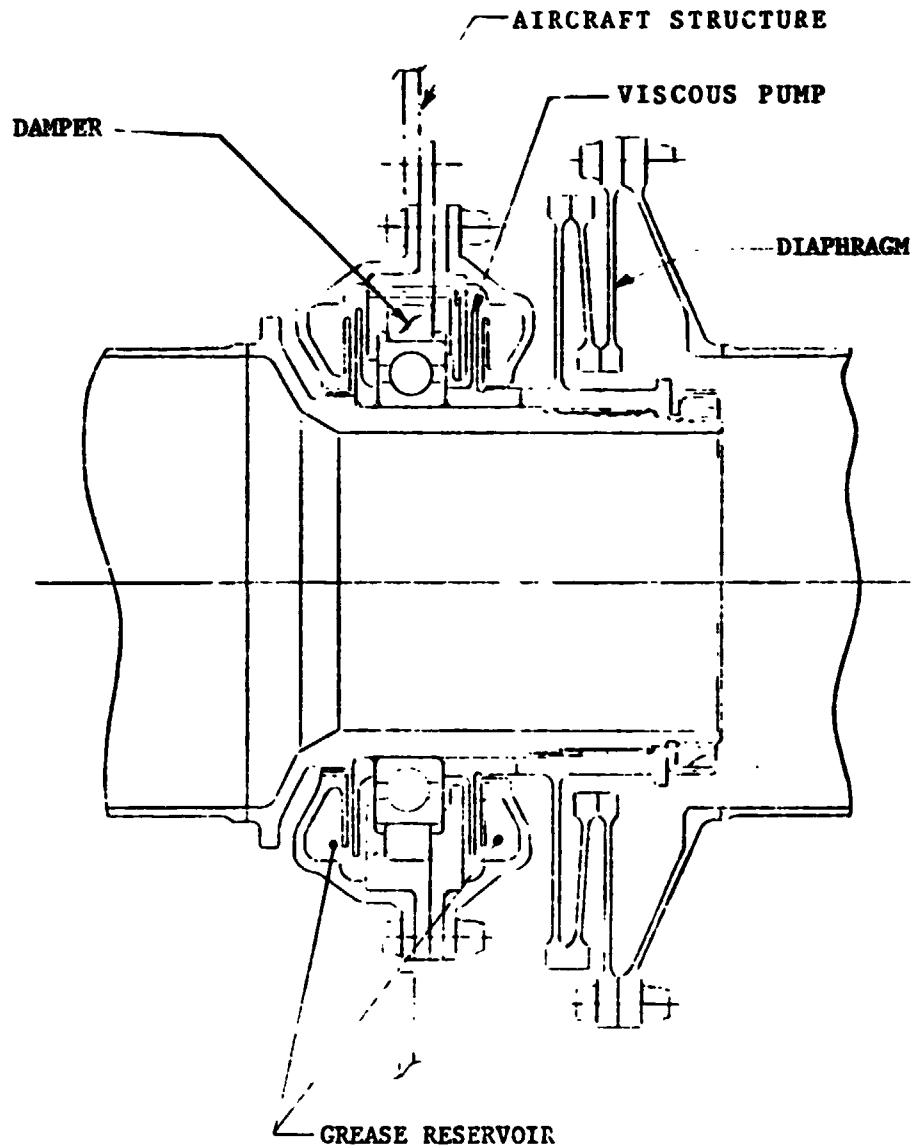


FIGURE 2.17 - LIFT FAN SHAFT MOUNT BEARING



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2.4 Weight and CG

Weight and center of gravity for the main shaft system components were determined and the results are presented in Table 2.18.

TABLE 2.18

RTA V/STOL SHAFT SYSTEM WEIGHTS AND C.G.'S

<u>Component</u>	<u>Weight (lbs)</u>	<u>CG Location (Station)*</u>
Combiner Box Assembly	412.8	278.0
Cross Shaft (each)	9.7	274.2
Center Engine Shaft	15.7	310.3
Fan Shaft (includes support bearings)	98.2	166.2
Totals	546.1	258.7

*Station Numbers are referenced to Figure 2.14.

2.5 Maintainability

2.5.1 Routine Service

Routine servicing of the RTA shaft system and combiner box will be limited to periodic checking of the oil level, normal oil changing and filter maintenance. The oil filter is provided with a pop-out indicator that will indicate the occurrence of high pressure drop across the filter. The combiner box will not be an oil consumer.

Oil change intervals are expected to be a function of the number of clutch engagement cycles and the resulting high bulk oil temperatures.

There are no components in the combiner box that will require periodic adjustment.

The grease lubricated bearings supporting the lift fan shaft are not expected to require short time interval maintenance. Their service requirements will, in part, be a function of the local temperature. The higher the temperature in that part of the airframe, the shorter a service interval predicted. Development testing of these bearings will provide good guidelines for grease lube life.



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2.5.2 Overhaul Requirements

In a production program, the combiner box would be subject to on-condition repair. This same approach, for a minimum cost program, would generally apply to the RTA program. It is expected that the combiner box would receive routine boroscope inspections with some disassembly being required for further inspection and/or repairs.

Combiner box disassembly and repair will require a limited number of special tools and technicians experienced in aircraft transmission repair procedures.

Combiner box components such as the disk clutch, over-running clutch oil pump, regulators and clutch control valve can be removed without a complete disassembly.